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HYDRAULIC MEASUREMENTS

BY THE SAME AUTHOR

A TEXTBOOK OF APPLIED HYDRAULICS

HYDRAULIC MEASUREMENTS

A MANUAL FOR ENGINEERS

BY

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PREFACE

THIS book is an amplification of the last chapter of the author's earlier work, *A Textbook of Applied Hydraulics*. The adequacy of that particular chapter was questioned by one or two reviewers because certain aspects of hydraulic measuring technique had been omitted from it, and because the methods actually mentioned were treated in varying degrees of detail. When preparing the second edition of *Applied Hydraulics* the author tried his best to remove these objections, but found no way of expanding the chapter to the suggested extent without throwing it out of scale with the rest of the book. In the end it seemed that the only solution of the difficulty was to write a completely new book. As no record could be found of any other publication with the title *Hydraulic Measurements* it certainly appeared likely that engineers might find such a work useful, especially as many of them are becoming more and more concerned in the accurate estimation of liquid flow. In Civil engineering, the formation of Drainage Boards and the growing need in Great Britain for the conservation of municipal water supplies have directed closer attention to stream gauging, while in Mechanical and Industrial engineering the immense increase in the use of liquid fuels, for example, has stimulated advances in the metering of piped discharges. The concurrent progress during the past twenty years in the study of the scientific laws of hydraulic flow has meantime provided a more stable basis on which to found a technique of flow measurement applicable to industrial conditions.

Where this book differs from some other works on flow measurement is that it deals with liquids only. When fundamental principles are being expounded it is no doubt advantageous to study fluids as a whole, including both gases and liquids; and manufacturers whose products can be adapted

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for metering either gases or liquids naturally find little need for delimiting the two zones. But an individual engineer faced with a specific problem, such as gauging the flow of a particular liquid in a particular pipe, does not want to be confused with the additional complexities that the measurement of elastic fluids involves. In any event the great variety of books on electrical measurements supplies the justification for a book with the analogous title of hydraulic measurements.

To hope that by limiting its range the treatment is going to be made simple is to imagine a vain thing. Even if authorities could agree among themselves, the results yielded by hydraulic measuring methods would be subject to uncertainty, and the appliances themselves would be sufficiently diverse and hard to classify. But experienced engineers are very far from being in unison. On the contrary, contradictory opinions are expressed and maintained with a warmth associated ordinarily with political convictions; whereas one official will put unqualified trust in the performance of a certain instrument, another official of equal standing will flatly refuse to accept any measurements made with that type of instrument. Nor are these conflicting views unreasonable when it is realised that the large-scale measurement of liquids is an art as much as a science, and that the worth of the figures that purport to represent the flow can only properly be assessed when the experience, skill, and reputation of the observers and of their chief are known. Besides, what is usually being measured is not a uniform and smoothly flowing stream of liquid, but a turbulent procession of swirling, eddying liquid elements, each following its own devious and incalculable path. Thus the numeral expressing the rate of flow is really no more than a statistical average.

The task of offering guidance through a region so beset by perplexities and baffling inconsistencies is not lightened by the knowledge that the authorities whose word must be cited are divided by not merely local but by international boundaries. For example, in Continental Europe the current meter is held in high esteem for making all kinds of measurements in which it will possibly serve, whereas in America this instrument is not favoured except for stream gauging. Again, of the two main types of current meter one is almost invariably preferred in countries where the English language or English influence

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prevails, while elsewhere the other type is exclusively used. It follows that an author must always be conscious that the simplest statement he makes may be controversial, and he has to ask the forbearance of readers if they find the opinions he expresses or cites are contrary to their own experience.

A more attractive aspect of the art of liquid measurement is that the necessary apparatus is often exceedingly simple. An opening cut in a sheet-metal plate, and a length of glass tubing, form the constituents of a number of trustworthy measuring appliances, which can thus often be improvised with the resources to be found in any small repair workshop.

In regard to the book itself, it is intended to be wholly practical so as to be of the greatest utility to those actually engaged in making hydraulic measurements, whether under laboratory or under service conditions. Although some elementary knowledge of hydraulic principles is naturally assumed, a glossary has been prepared for readers who have specialised in other branches of engineering. The frequent use of metric units, and the comprehensive table of conversion factors that is given, together give a clear indication of the author's preferences; water measurement especially shows up the unhandiness of the foot and the pound in comparison with the slick interchangeability of the litre and the kilogram. As the book deals with measurements rather than with measuring instruments the illustrations are generally to be regarded as diagrammatic only. For the information on which many of the diagrams are based the author wishes to express his cordial thanks to the following firms: he would like to think that such help as their clients may receive from the book will serve as some slight indirect return for their kind co-operation:—

Messrs. Baldwin-Southwark Corporation.

„ Bopp & Reuther.

„ The British Pitometer Co., Ltd.

„ The Budenberg Gauge Co., Ltd.

„ Dobbie, McInnes, Ltd.

„ The Drayton Regulator and Instrument Co., Ltd.

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„ Elliott Bros. (London), Ltd.

„ Evershed & Vignoles, Ltd.

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Messrs. Guest & Chrimmes, Ltd.
„ Kelvin, Bottomley & Baird, Ltd.
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„ Dr. A. Ott.
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„ Tecalemit, Ltd.
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The author is also greatly indebted to individuals and institutions, and especially to Prof. J. N. Le Conte, Mr. R. W. S. Thompson, M.Inst.C.E., the National Physical Laboratory, Teddington, and the National Hydraulic Laboratory, Washington. The Bibliography must serve as an acknowledgment of the assistance received from publications and periodicals; but this cursory treatment is particularly inadequate as an expression of appreciation of one such publication, namely the *Fluid Meters* Report of the American Society of Mechanical Engineers. This admirable specialised production sets a standard that writers of general treatises cannot hope to reach.

With this comparison in mind the author is conscious that in trying to cover the whole range of hydraulic measurements his book is hardly more likely to be exhaustive than the original chapter on which it is based. So he must get whatever encouragement he can from two advantages which residence in Egypt should confer on him. The detached yet not too remote situation of the country offers opportunities of impartially presenting the diversity of views prevailing in two hemispheres; and the country not only gave birth to the art of hydraulic measurement several thousand years ago but has been the scene in recent years of classic experiments which have notably advanced the art.

HERBERT ADDISON.

GIZA, January, 1940.

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INTRODUCTORY

	§ No.		§ No.
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1. Definition of Hydraulic Measurements. In this book the term *Hydraulic Measurements* is intended to cover the measurement or the estimation of the level, pressure, volume, weight, and rate of discharge of liquids under all ordinary engineering conditions. It includes only incidentally physical measurements such as those of density, temperature, and viscosity, it makes no attempt to deal with allied hydrological measurements such as those of rainfall and evaporation, and the measurement of gases of all kinds is specifically excluded. Neither has it been possible to mention the automatic controlling and regulating appliances that so often work in conjunction with flow-measuring apparatus.

Although the liquid whose pressure or discharge is to be gauged will usually be water, the treatment throughout the book has been kept as general as possible, so that it will often apply to other industrial liquids, such as oils and spirits.

2. System of Classification. The engineer faced with a particular problem of measurement is more likely to be concerned with the immediate conditions in front of him than with the fundamental principles governing the operation of the instrument he will ultimately choose. To begin with he may only know that the liquid is working under a high pressure, or that it is flowing along an open channel, or that only unskilled attendants will be available for taking readings. This explains the system of classifying hydraulic instruments that has here been adopted; it is intended to guide the reader quickly to the chapter wherein he may find methods likely to suit specific circumstances.

Unfortunately, reference to one chapter only will frequently not be enough. A complete gauging installation may have to

be built up from a number of individual components having different functions and described in different parts of the book. It would be impossible in a volume of this size to catalogue the very large number of permissible combinations of these components; but the agility enforced on the reader in forming his own scheme is mitigated by the provision of copious cross-references and a complete index.

3. Notation and Units. In the absence of an international system of notation it has not been practicable to choose mathematical symbols that will agree with each of the various

Units of Length and Head	Units of Area	Mean Value of Acceleration of Gravity, g	Value of $\sqrt{2g}$	Units of Velocity	Units of Rate of Flow or Discharge
Foot (ft.)	Sq. ft	32.2 ft per sec. per sec	8.03	Feet per second	Cubic feet per second (cu. ft./sec.)
Centimetre (cm.)	Sq. cm	981 cm. per sec. per sec	44.3	Centimetres per second	Cubic centimetres per sec. (cu. cm./sec.)
Decimetre (dm.)	Sq. dm.	98.1 dm per sec. per sec.	14.00	Decimetres per second	Litres per sec (lit./sec.)
Metre (m.)	Sq. m.	9.81 m per sec. per sec.	4.43	Metres per second	Cubic metres per second (cu. m./sec.)

national systems, but efforts have been made to ensure correspondence whenever possible. Each symbol is explained when first it is introduced, and a complete key is given on page 280.

In general, lengths are expressed in *feet* and discharges in *cubic feet per second*. No attempt has been made to supply factors for each formula for converting discharges to Imperial gallons per minute, United States gallons per day, litres per second, or the like, because the Conversion Table on pp. 281–282 will take care of all such computations. The intention has been rather to leave flow formulæ in the original form which reveals their mathematical basis, and whenever possible to express the numerical factors and coefficients that are so regrettably plentiful, in the form of *ratios* (pure numbers) whose

values are independent of the system of units. As a typical flow formula involves only terms expressing length, time, volume, and the acceleration of gravity g , it is valid in its basic form for *all consistent systems of units* so long as the empirical coefficient is left as a ratio and so long as the value of g is correctly expressed. The table above gives the values usually likely to be wanted

CHAPTER I

DIRECT MEASUREMENT OF DEPTH, HEAD, AND PRESSURE

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4. Purpose of Instruments. The devices and methods described in this chapter have as their object either—

(i) To measure the depth of liquids, i.e. to indicate the position of the free surface of a liquid with reference to some fixed datum plane ; or

(ii) To measure the pressure or the pressure head at a given point in a liquid ; or

(iii) To measure the differential pressure or the differential head between two points in a hydraulic system.

If h is the pressure head or the head at the given point,

p is the pressure at the point,

w is the density of the liquid in terms of weight per unit volume,

then the relationship between these quantities can be expressed thus :

$$p = wh \quad . \quad . \quad . \quad . \quad (1)$$

Example : What is the pressure in pounds per square inch at the bottom of a tank containing oil of specific gravity 0.92, if the depth of oil is 12 ft. 8½ ins. ?

$$\begin{aligned} \text{Here} \quad h &= 12.71 \text{ ft.}, \\ w &= 0.92 \times 62.4 = 57.3 \text{ lbs./cu. ft.}, \\ \text{therefore} \quad p &= 57.3 \times 12.71 = 730 \text{ lbs./sq. ft.} \\ &= \frac{730}{144} = 5.07 \text{ lbs./sq. in.} \end{aligned}$$

For fresh water at ordinary atmospheric temperatures the following values are usually sufficiently accurate :—

1 foot head is equivalent to a pressure of 0.434 lb./sq. in.

1 metre head „ „ „ 0.100 kg./sq. cm.

But it should be noted that the density of all liquids—especially organic compounds such as oils and spirits—is appreciably affected by temperature changes, and therefore to make a completely accurate conversion of head to pressure, or *vice versa*, the temperature of the liquid must be known (e.g. for water, see page 282).

DEVICES WHICH DIRECTLY SHOW THE POSITION OF THE LIQUID SURFACE

5. Depth or Staff Gauges. Here the position of the free surface is directly read off by means of a graduated scale immersed in the liquid (Fig. 1). At I a wooden post is shown driven into the bed of a stream ; or instead of a scale of feet painted on the post, there may be graduations engraved on the vertical faces of bridge piers, abutments, or the like. Where a big range of levels has to be read at a point on a sloping river or canal bank, a stairway may be formed as in Fig. 1 (II), having engraved marble or stainless metal slabs sunk flush in the vertical sides of the stairway. The enlarged detail in the sketch shows a form of easily read scale which permits the water level to be estimated to the nearest centimetre.

Accurate reading of staff gauges is only possible if the liquid is at rest or nearly so ; in moving streams, wave action or heading-up against the gauge itself may create difficulties. These can be minimised by fixing the gauge in a gauge-well communicating by means of a pipe with the river or canal, and provided with a ladder for the observer (Fig. 1 (III)). Undesirable fluctuations of level are thus damped out.

To make it easier for an observer to read staff gauges when looking down on to them from above, they may be set in an inclined position, the graduations being modified accordingly.

When, as in river and stream gauging, it is necessary to link up the gauge readings with the datum levels of the surrounding country, then surveying methods must be used to establish the height of the gauge marks in relation to the nearest bench mark or other fixed datum point.

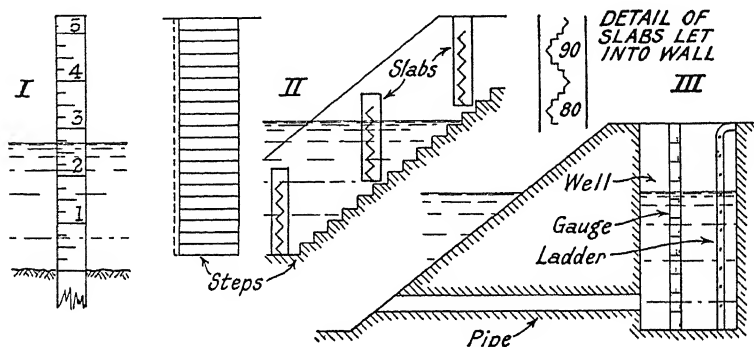


FIG. 1.—Staff gauges.

6. Sounding Rods, Sounding Wires, and Dipsticks.

A sounding rod is essentially a portable staff gauge; when it is lowered into the vessel or stream whose depth is required, with its foot resting on the bottom (Fig. 2 (I)), then the depth of liquid can be read off against the graduations on the rod. Naturally the rod must be held as nearly as possible vertically; and if the stream bed is soft or yielding, then a wooden or metal foot must be fitted to prevent the bottom of the rod from sinking in.

For quickly flowing streams in which a sounding rod would be unmanageable, a sounding wire is necessary—the equivalent of the nautical lead-line. In very deep, swift rivers, the horizontal thrust of the water on the wire and on its weight or sinker sweeps the wire into a curved or bowed shape appreciably out of the vertical, no matter how heavy the weight is (Fig. 2 (II)). A correction is therefore necessary, which has the following values for a wire 1.6 mm. diameter and a conical weight of 106 lbs.⁽¹⁾ * :—

* (1) these are references to the Bibliography, page 287.

Mid-depth Stream Velocity (Ft per sec)	Observed Sounding in Feet				
	10	20	30	40	
4	—	—	—	0.1	Correction in feet to be subtracted from observed sounding.
6	—	0.1	0.2	0.3	
8	—	0.2	0.4	0.7	
10	0.1	0.3	0.8	1.4	

Such sounding wires are almost always paid out from a winch whose barrel has circumferential scales and pointers, in the manner shown in Fig. 2 (II), as it would be inconvenient to

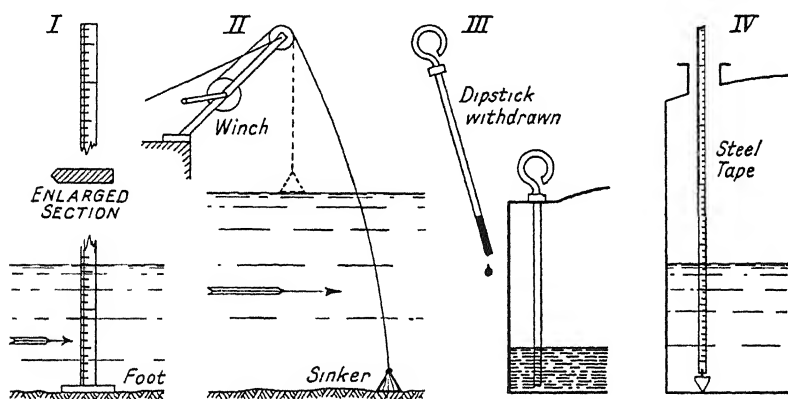


FIG. 2 —Sounding rods, sounding wires, etc.

graduate the wire itself. The weight is first lowered until its base just touches the water surface, and a reading on the scales is taken, then the weight is lowered into the stream until it touches the bottom and a second reading is taken. The difference between the two readings, corrected if necessary as described above, gives the required water depth. As the whole operation may have to be carried out from a boat which provides by no means a steady platform, errors up to $\pm \frac{1}{4}$ ft. or more may easily arise.

Dipsticks and dipwires are used for measuring the depth in closed vessels where the liquid surface is invisible; the reading is taken after the stick is removed from the vessel, by noting the trace of liquid left on it (Fig. 2 (III)). A familiar example

is the dipstick of an automobile-engine sump, though here the datum point is not the bottom of the vessel, but the facing on the crankcase on which the collar on the dipstick rests. A weighted steel tape is convenient when gauging the oil level in large storage tanks (Fig. 2 (IV)), for it is possible to feel quite sensitively when the weight makes contact with the tank bottom, and when the tape is withdrawn the oil trace on it may be read with an error of not more than $1/200$ ft.

7. Hook and Point Gauges. In experienced hands these instruments can determine the position of liquid surfaces with great accuracy: usually the error can easily be kept within limits of $\pm 1/1500$ ft.—say 0.2 mm., and many observers claim greater precision. On the other hand, the gauges are only suitable for a limited range of levels—not more than a few feet. The essential element is a pointed brass rod which can be set with its tip exactly in the liquid surface: if the rod points upwards the instrument is called a *hook gauge* (although there is no real necessity for the rod to be bent into a hook), while if the rod points downwards we have a *point gauge*.

A typical hook gauge is sketched in Fig. 3 (I). Mounted on a firm support above the liquid is a frame in which a graduated metal stem can slide vertically, and inserted axially in the stem is the round wire shank of the hook itself. A clamping screw C_1 fixes the shank after it has been drawn in or out of the stem to suit the desired range of liquid levels. When the upper clamping screw C is released the stem and hook may be moved so as to bring the tip roughly into the liquid surface, the final adjustment being made, after clamping C , by the use of the slow-motion screw F .

As shown at (II), Fig. 3, the tip of the point gauge is lowered on to the liquid surface from above, otherwise it resembles the hook gauge. As a rule it is only to be preferred to the hook gauge when flowing water is to be observed, where the hook gauge would create undesirable disturbances.

Various modifications which permit the hook gauge also to be used for measurements of moving water are illustrated in Fig. 3. If the current is slight, or if there are small surface ripples, then the point may be protected by a little sheet-metal shield soldered to the shank as shown at (III), with a few small holes to give the necessary damping effect. A hook gauge is

shown at (IV) mounted in a glass gauge well which is connected to the main tank or channel by rubber or metal tubing. Differential hook gauges of this type are referred to in § 16. In Fig. 3 (V) the hook is fixed relatively to the gauge well, which here takes the form of a metal chamber with parallel glass sides; the whole chamber may be moved up and down a graduated column with the necessary clamping screws C and C_1 , slow-motion screw F , and vernier. A mirror directs a strong light on to the tip of the "hook," and a magnifying eyepiece is fitted for observing it. Although perhaps the most sensitive type of hook gauge, this instrument is unsuitable for taking

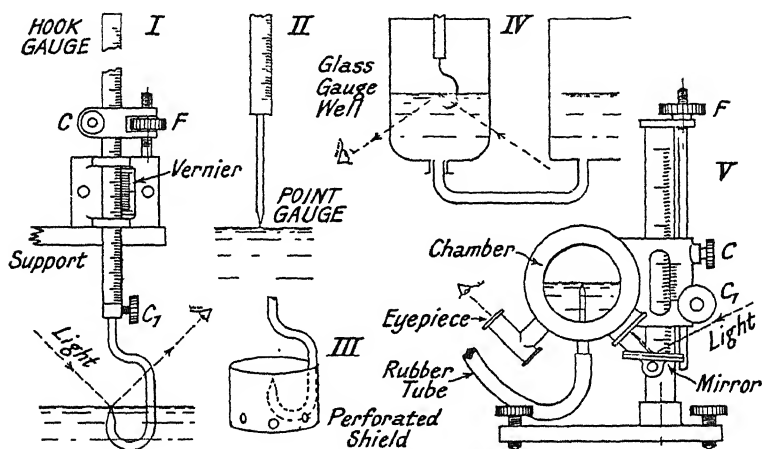


FIG. 3.—Hook and point gauges.

readings in rapid succession because of the time taken for the water to flow through the rubber connecting tube and to stabilise its level in the chamber after each adjustment.

8. Use of Hook and Point Gauges. There is no advantage to be gained by making the tip of the hook or point gauge too sharp: it should not be needle-sharp, but rounded to a radius of perhaps $1/100$ in. Its position cannot be accurately observed without good and well-directed illumination. Strong daylight or electric light should fall on to the water surface and be reflected into the observer's eye as suggested in Fig. 3; the tip of the gauge is first sunk beneath the liquid surface and then very gradually raised by the use of the slow-motion screw F

until it appears as a tiny black speck in the midst of the illuminated area. By means of the vernier the scale reading may then be taken.

If the gauge is mounted in a glass chamber then the light should preferably be reflected from the underside of the water surface (Fig. 3 (IV) and (V)). If the eye is held at the proper level, the inverted image of the tip of the gauge can be seen brilliantly reflected, and the tip is slowly raised until it just seems to touch its image: the tip will then be exactly in the water surface.

When point gauges are used in conjunction with flowing water, the moment of contact is shown, as the tip is lowered, when a train of tiny ripples is set up. A good deal of judgment has here to be used, because the surface of a flowing stream is hardly ever completely steady, consequently one can hardly hope for more than a fair average position of the tip. Electrical detection methods for point gauges are mentioned in § 34.

It is rarely possible to read directly from the scale of the hook gauge the depth or liquid level that is required; instead, the actual gauge reading is compared with the zero reading taken when the liquid surface is exactly level with some fixed datum point, the difference between the readings giving the desired height of the actual liquid surface above the datum point. Methods of taking zero readings are described in §§ 86, 87 and 176.

9. Float Gauges. These gauges, which have a very wide range of application, all employ a float of wood, cork, or (usually) hollow zinc or copper which rides on the liquid surface and rises or falls with it. Although hardly yielding such precise results as hook gauges, they are much less dependent on the personal skill of the observer, and they will measure much greater differences of level.

In the simple embodiment shown in Fig. 4 (I) the float is guided by two lugs working freely on a pair of vertical rods, and its movements are indicated by a graduated scale—a box-wood metre scale serves very well—passing freely through a slotted upper guide. If the ballast weight below is adjusted so that the whole floating member just rides vertically when unguided, the friction at the three points of constraint need

be very small, and the level in the tank may therefore be measured with an error of hardly more than $\pm 1/1000$ ft.

The relatively crude arrangement shown at (II) is often good enough for showing the depth of water in overhead tanks ; here a counterweight moving over an external scale serves as an indicator. The system can be made suitable for precision work by using a large and accurately balanced pulley mounted on anti-friction bearings ; in Fig. 4 (III) the float moves in an independent float chamber, the scale above it works against a vernier, and a stranded bronze wire connects the float and the counterweight. Alternatively, scale readings may be taken by means of a surveyor's level mounted on a column nearby,

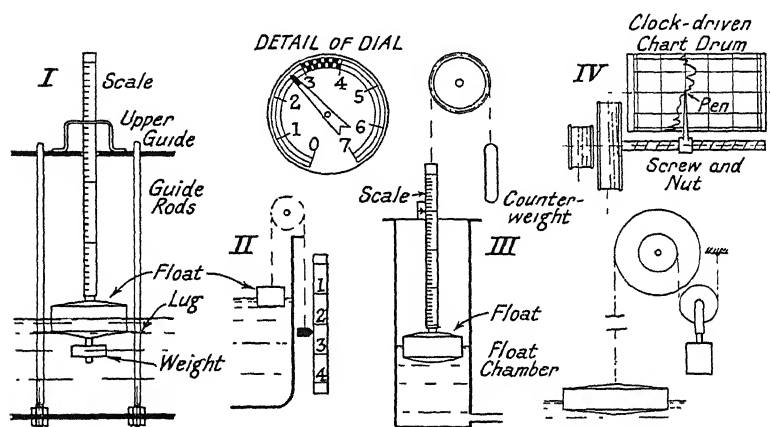


FIG. 4.—Float gauges.

and another plan is to replace the linear scale by a circumferential dial. As shown in the detail sketch, a pointer on the spindle of the pulley works against circumferential graduations, so making it possible to magnify the float movement. Another interesting variant makes use of a graduated glass scale as the counterweight, an optical system projecting a magnified image of the graduations and of the fixed index mark on to a distant screen near the experimenter's control post.⁽²⁾

10. Float Gauges (continued). Among possible sources of error likely to affect float gauges are—

(i) Mechanical friction in the guiding and indicating mechanism. This can be brought within virtually negligible

limits by careful design, especially by making the float of generous size—say 1 ft. diameter or more.

(ii) When the float is connected to a counterweight by a cord, tape, or chain passing over a pulley, as in Fig. 4 (II) and (III), a float movement of (say) 1 ft. will alter the effective weight of the float by an amount equal to the weight of 2 ft. of cord or chain, and the immersion of the float will vary accordingly. Usually the variation is insignificant, but if the connecting medium is a graduated steel measuring tape, a correction of 0.2 per cent. or more may have to be applied. As pointed out below, the counterweight itself must not be allowed to dip into the liquid.

(iii) If the density of the liquid varies, as a result either of change of temperature or change of liquid, then the buoyancy of the float will be modified, with a corresponding change in the reading of the scale. Provided the immersed depth of the float is small—say 1 or 2 in.—temperature changes of a given liquid will rarely produce any sensible effect.

Recording Float Gauges. Float-operated, self-recording gauges are extensively used for giving a record of the depths of reservoirs, tanks, etc. An example is shown diagrammatically in Fig. 4 (IV). The stranded wire from the float is wound on to a drum mounted on a screwed spindle, so causing the pen mechanism geared to it to move proportionately to the movement of the water surface. A paper chart fixed on a clockwork-driven drum forms the record on which depth is automatically plotted against time. The counterweight wire here works on a separate and smaller drum, the system being designed to reduce the travel of the counterweight as much as possible, so that even at top water level the weight is not immersed. If immersion did accidentally occur an appreciable error might result due to the reduction in the effective weight of the counterpoise.

It may often be advisable to protect the floats of recording gauges from surface waves and similar disturbances, either by providing a float chamber as in Fig. 4 (III), or by the use of a pair of guide wires, weighted at the bottom, serving the same purpose as the guide rods shown in Fig. 4 (I).

The methods by which floats may be made to operate

distant-reading indicators and recorders are described in Chapters II and XIII.

11. Displacer Gauges. Although displacer gauges can hardly be said to indicate directly the position of the liquid surface, they can certainly be used when a free liquid surface is available and can thus sometimes take the place of float gauges. The displacer is usually cylindrical, made of material whose density is greater than that of the liquid, and it is hung from a spring balance or its equivalent which measures the effective weight of the cylinder (Fig. 5 (I)); thus, as the liquid level rises, the needle of the balance moves as the upthrust of the liquid on the displacer increases, and it becomes possible to calibrate the scale of the balance in terms of liquid level.

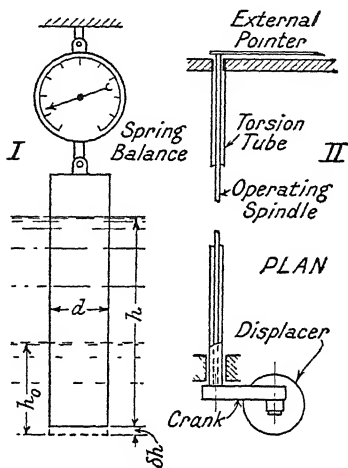


FIG 5.—Displacer gauges.

Example : A cylindrical displacer 5 ins. diameter is hung from a spring balance whose hook moves $\frac{1}{4}$ in. when the load increases by 10 lbs. If the displacer is immersed in acid of specific gravity 1.25, what change of balance reading will correspond to 1 ft. change of liquid level ?

Let a be the cross-sectional area of the displacer, and let δh be the amount by which the displacer sinks when the acid level falls by 1 ft. (see Fig. 5 (I)).

Then change of upthrust = $W = wa(h - h_0)$.

Also $h + \delta h - h_0 = 1$, or $h - h_0 = 1 - \delta h$.

Substituting, $W = wa(1 - \delta h)$.

Now if the hook of the balance rises $\frac{1}{4}$ in. for a reduction of load of 10 lbs., the rise δh for a reduction of load W will be

$$\delta h = \frac{W \cdot \frac{1}{4}}{10 \times 12} = \frac{W}{480} \text{ ft.}$$

Substituting in the above expression for W , we find

$$W = \frac{wa}{1 + \frac{wa}{480}}.$$

Inserting now the values $a = \frac{\pi}{4} \times \left(\frac{5}{12}\right)^2 = 0.136$ sq. ft., and $w =$ density of acid $= 62.4 \times 1.25 = 78.0$ lbs/cu. ft., we find $W = 10.35$ lbs = change of balance reading corresponding to 1 ft. change in level. That is, 1 lb. on the balance scale represents 0.0965 ft., and a scale reading directly in feet could thus be constructed.

It will be noted that displacer gauges, unlike the other types of liquid level gauge so far described, give indications that depend directly on the density of the liquid. On the other hand, they have the advantage, when measuring corrosive liquids and the like, that the only element in contact with the liquid is of very simple form.

A suggestion for a displacer gauge ⁽³⁾ operating in a closed vessel, e.g. the drum of a high-pressure steam boiler, is given in Fig. 5 (II). The displacer is hung from a crank fixed on the inner end of a horizontal torsion tube which acts as the elastic element for measuring the effective weight of the displacer. At the outer end the tube is secured in the vertical wall of the vessel. An operating spindle passes axially through the tube, clamped to the crank at the inner end and carrying at its outer end a pointer, moving over an external scale, which gives the indications of liquid level. The absence of packed glands, minimising friction and preventing leakage, is a valuable advantage of this system.

Differential displacer gauges are described in § 214.

GLASS-TUBE GAUGES

This section deals with pressure, head, and level gauges in which the reading is taken directly from a visible column of liquid in a glass gauge-tube.

12. Piezometer Tubes. An open-topped glass tube connected at its lower end to the vessel containing the liquid to be measured is called a piezometer tube and forms the simplest type of glass-tube gauge (Fig. 6 (I)). The level is read off directly from a scale fixed behind the tube; if liquid levels or heads are wanted, the scale is graduated in units of length, but if pressures are to be read off, the density of the liquid must be taken into account (§ 4). Because of the effect of surface tension the liquid in the tube may not stand at exactly the

same level as the liquid in the containing vessel, the difference depending on the nature of the liquid and on the diameter and degree of cleanliness of the tube. Thus, water in a tube $\frac{1}{4}$ -in. bore will stand 0.18 in. *higher* in the piezometer than in the vessel.⁽⁴⁾ The safest plan is to avoid such possibilities of error by using big tubes—not less than $\frac{5}{8}$ in. diameter for water and not less than $\frac{3}{8}$ in. diameter for mercury.

If the liquid level in closed vessels under pressure is to be measured, then the top of the gauge tube must be connected to the top of the vessel—a familiar example is the ordinary water gauge used on steam boilers. In certain industrial operations where the liquid would solidify or would vaporise if exposed in a sight-glass at atmospheric temperature, the sight-glass may be jacketed and the liquid kept at the desired temperature by circulating hot or cold water through the jacket.⁽⁵⁾

13. Gauges using a Special Indicating Liquid. If the range of level to be measured is so great that a simple piezo-

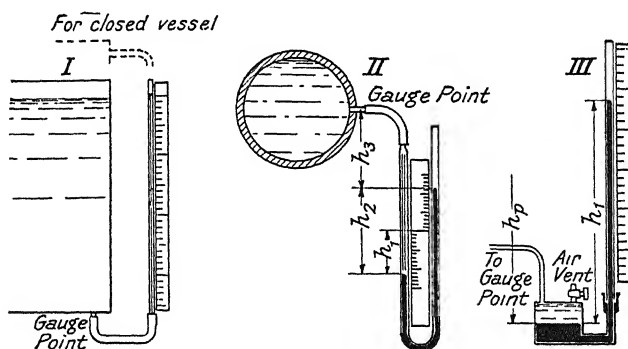


FIG. 6—Glass-tube gauges.

meter tube would be inconveniently long, then a gauge containing a special indicating liquid, usually heavier than the liquid to be measured, may be used (§ 52).

(i) *Double-column manometer, or U-tube.* In Fig. 6 (II) a U-tube is shown measuring the pressure in a closed pipe. The liquid in the pipe, or in general the liquid whose level or pressure is to be measured, will be termed the *metered* liquid, to distinguish it from the *indicating* liquid in the gauge tube.

The relation between pressure changes at the gauge point and the movement of the indicating columns can be established thus :—

- Let w = density of metered liquid,
 w_i = density of indicating liquid,
 h = pressure head at gauge point,
 h_2 = corresponding deflection of gauge, i.e. vertical distance between tops of liquid columns,
 h_0 = vertical distance between zero of gauge (when indicating columns are at the same level, and deflection is zero) and gauge point.

It is assumed that the two legs of the U-tube are of the same diameter.

In the position of the columns shown in Fig. 6 (II), a column of indicating liquid of height h_2 is balanced by a column of metered liquid of height $h_2 + h_3$, plus a column of metered liquid equivalent to the head h at the gauge point.

Hence $w_i h_2 = w(h_2 + h_3 + h),$

but $h_3 = h_0 - h_1 = h_0 - \frac{h_2}{2}.$

From which $h = h_2 \left(\frac{w_i}{w} - 0.5 \right) - h_0 \quad . \quad . \quad . \quad (2)$

One advantage of the U-tube gauge is that it serves just as well for negative heads as for positive heads.

(ii) *Single-column manometer.* This instrument has the advantage over the plain U-tube that one liquid column only has to be read instead of two, one of the legs of the U-tube being opened out into a wide, shallow container in which only small changes of level occur (Fig. 6 (III)).

Let A = cross-sectional area of container,

a = cross-sectional area of sight-glass,

h_p = total head of metered liquid above level of indicating liquid in container, in position shown. (This includes head at gauge point plus head due to metered liquid in connecting pipe),

h_1 = corresponding height of column of indicating liquid,

h_2 = rise in indicating column corresponding to an increase of head h at gauge point.

In the original position of the gauge, $wh_p = w_i h_1$. The rise of the indicating column by the amount h_2 will depress the level of indicating liquid in the container by an amount

$h_2 \cdot \frac{a}{A}$, and consequently under the new conditions the equation of equilibrium is

$$w\left(h_p + h_2 \cdot \frac{a}{A} + h\right) = w_i\left(h_1 + h_2 + h_2 \cdot \frac{a}{A}\right).$$

By subtraction and simplification, we find

$$h = h_2\left[\frac{w_i}{w} + \frac{a}{A}\left(\frac{w_i}{w} - 1\right)\right] \quad . \quad . \quad . \quad (3)$$

Example : A single-column manometer has a container 4 ins. diameter and a glass tube $\frac{3}{8}$ in. diameter. The metered liquid is water and the indicating liquid is mercury. It is required to draw the scale from which head of water in feet can directly be read.

Here $\frac{a}{A} = \left(\frac{0.375}{4.0}\right)^2 = 0.0088$, and $\frac{w_i}{w} = \frac{13.59}{1.0} = 13.59$.

Therefore $h = 1 = h_2[13.59 + 0.0088 (12.59)]$, or $h_2 = 0.0731$, that is, 1 ft. head is represented on the scale by a distance of 0.0731 ft., and the scale can then be drawn as in Fig. 7.

14. Compound Manometer. A modification of the single-column manometer which makes it very suitable for indicating the water level in overhead tanks is illustrated in Fig. 8 (I). Below the container of the normal instrument is another container, the two being connected by a steel tube, the mercury column in the tube having a length h_4 adjusted to balance the column of water in the pipe connecting the overhead tank to the gauge at ground level. The tube must naturally dip below the mercury surface in the lower container. Using the symbols of Fig. 8, it can be shown that the change of head h at the gauge point is related to the corresponding movement h_2 of the water column in the sight-glass by the expression

$$h = h_2\left[1 + 12.6\left(\frac{a}{A_1}\right) + 12.6\left(\frac{a}{A_2}\right)\right] \quad . \quad . \quad (4)$$

Thus, by making the mercury containers sufficiently large, the movement of the indicating column will reproduce, almost full-size, the movements of the water surface in the overhead tank. The scale can thus be very much more open than would be possible with the standard single-column mercury gauge

shown in Fig. 6. By substituting for the water in the sight-glass of the compound gauge a liquid of slightly less density than water, the gauge can be made to show exactly full-size the movement of the water surface in the overhead tank.

The alternative arrangement of compound gauge represented in Fig. 8 (II) uses a wide-bore U-tube surmounted by a narrow indicating column, but its principle of operation differs in no way from that of type (I).

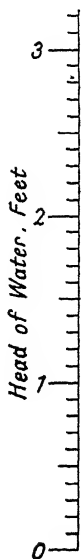


FIG. 7.—Scale for single-column manometer (actual size).

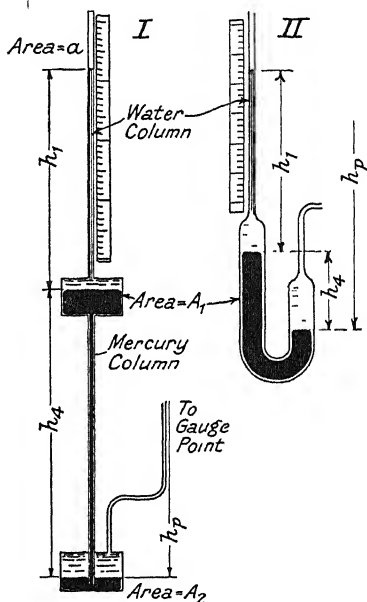


FIG. 8.—Compound manometers.

15. Differential Gauges. These are required for measuring the *difference* between the pressure or head at two points in a system; they take no account of the absolute values of these quantities. The instruments in Fig. 9 are shown measuring the frictional loss of head in pipes, but a more common use of differential gauges is as *secondary elements* for measuring the differential head generated by the primary elements of flow meters (§ 110). Often two open-topped piezometer tubes mounted side by side will serve, although in many instances it is necessary to couple the tops of the tubes by an air-tight cap

as in Fig. 9 (I). By working the air-pump P (a bicycle-tyre pump serves very well), or by slightly opening the vent-cock V , the observer can bring the liquid columns to the desired part of the scales. The observed difference h between the height of the indicating columns truly represents the differential head, except when the absolute pressure is so high—say 20 atmospheres or more—that the density of the compressed air above the liquid columns becomes appreciable. The air must then be taken into account as though it were the indicating liquid

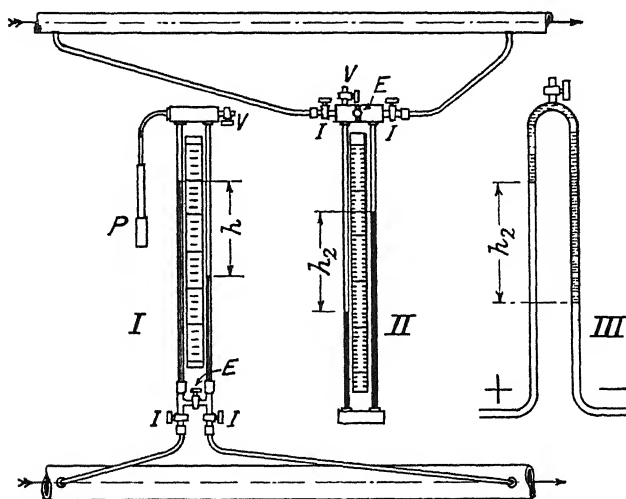


FIG. 9.—Differential manometers

used in the inverted U-tube gauge (Fig. 9 (III)). (See also § 17.)

Referring now to Fig. 9 (II), this shows a U-tube differential gauge or double-column gauge; it uses an indicating liquid whose density w_i is greater than that of the metered liquid w , and consequently the relationship between the observed deflection of the gauge h_2 and the desired differential head h is

$$h = h_2 \left(\frac{w_i}{w} - 1 \right) \quad . \quad . \quad . \quad (5)$$

By suitably choosing the density of the indicating liquid, therefore (§ 51), the observed difference between the height of

the indicating columns may be either greater or less than the differential head of metered liquid.

Example · A U-tube differential gauge is required to measure a differential head of 1 metre of water. What will be the deflection of the gauge if the indicating liquid is (i) mercury, (ii) carbon tetrachloride of specific gravity 1.60 ?

Using the above relationship, the deflection is found to be (i) 7.95 cms., (ii) 167 cms.

The purpose of the cocks *E*, *V*, and *I* is explained in § 45.

The inverted U-tube differential gauge (Fig. 9 (III)) uses an indicating liquid lighter than the metered liquid, but the relationship (formula 5) between the differential head and the deflection h_2 is just the same as it is for the U-tube gauge (II). As a rule personal preference alone decides whether the U-tube or the inverted U-tube should be used for measuring small differential heads.

16. Other types of Double-column Differential Gauge.

(i) *Differential hook gauges*. If the gauge tubes of the piezometer type of gauge (Fig. 9 (I)) are increased in diameter, they can take the form of gauge wells in each of which a hook gauge can be mounted as in Fig. 10 ; and to avoid the need for reading each hook gauge separately, the stem of one gauge may have an arm fitted with a vernier working against a scale clamped to the stem of the other gauge. A connection for an air-pump *P* will usually be needed, and also, of course, some type of slow-motion screw *F* as described in § 7. The symbols + and — by which the connecting pipes are distinguished in this and other diagrams do not signify that the pressures there are necessarily positive and negative; the + sign shows the greater or upstream pressure, and the — sign the lesser or downstream pressure.

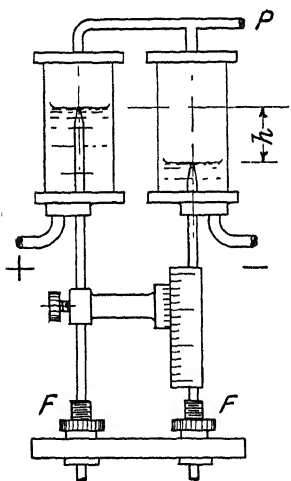


FIG. 10 —Differential hook gauges.

and negative; the + sign shows the greater or upstream pressure, and the — sign the lesser or downstream pressure.

The differential hook gauge may serve as an inverted U-tube gauge if an indicating liquid lighter than water is used

above the measuring columns, as in Fig. 9 (III). By taking special care in directing the lighting on to the tips of the gauges (§ 8), the moment at which the point breaks through the surface of separation can be established just as precisely as in the normal hook gauge (Fig. 3 (IV)). Probably no other type of gauge of corresponding simplicity will give, in sympathetic hands, such reliable measurements of small differential heads.

If the absolute pressures concerned are very high there may be difficulties in finding strong enough large-bore glass tubing to serve with safety as the gauge wells; in such conditions the gauge wells may each take the form of a parallel slot in a steel plate with a heavy plate-glass window on either side.⁽⁶⁾

(ii) *U-tubes in series.* Fig. 11 shows how U-tube gauges may be arranged in series, so permitting relatively large differential heads to be accurately measured; for practical reasons it is often better to have a number of short indicating columns rather than a single pair of very long ones, although, of course, the labour of reading the gauge is increased, for each column of the series must be separately observed, and the individual differential heads summed together to find the total head difference.

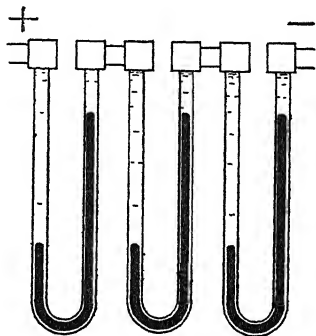


FIG. 11.—U-tubes in series.

17. Single-column Differential Gauges. (i) Just as a simple modification transformed the U-tube gauge (Fig. 6 (II)) into the U-tube differential gauge (Fig. 9 (II)), so the single-column manometer (Fig. 6 (III)) can be made to serve as a differential manometer (Fig. 12 (I)); all that is required is to connect the top of the indicating tube to the negative gauge point, and to add vent and equalising cocks (§ 45). The presence of a column of metered liquid above the indicating liquid in the gauge tube calls for a modification also of the basic relationship, which now has the following form:—

$$h = h_2 \left(1 + \frac{a}{A} \right) \left(\frac{w_2}{w} - 1 \right). \quad . \quad . \quad (6)$$

In this equation h_2 represents the height of the indicating column above the zero point of the scale, corresponding to a differential head h of metered liquid. The zero setting can be simplified by giving the scale a small vertical adjustment: when the differential head falls to zero (which it can be made to do by opening the equalising cock E and closing the isolating cocks) the zero point of the scale can be set opposite the indicating column, and clamped there. A single-column gauge calibrated for flow metering is described in § 215.

(ii) Comparing the double-column differential gauge (Fig. 9 (I)) with the single-column gauge (Fig. 12 (II)), we see that the chief difference is the addition of an upper container or air vessel

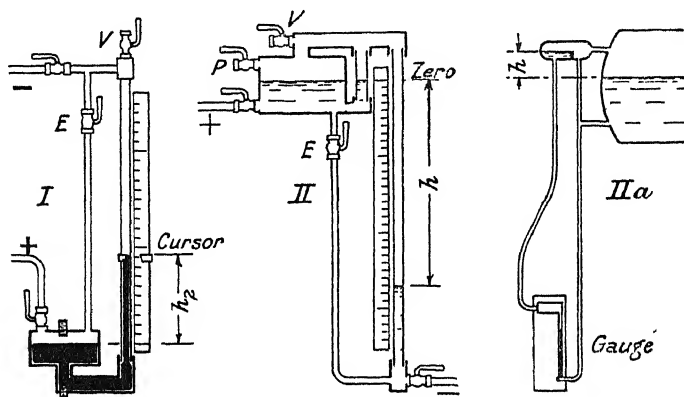


FIG. 12.—Single-column differential gauges.

set in parallel with the left-hand or positive indicating tube, which is now a short sight-glass only and has no graduated scale. Readings are taken, directly in terms of differential head, from the single scale which is graduated from the top downwards; and before any reading is taken the scale is adjusted slightly up or down until its zero mark is opposite the liquid level in the left-hand sight-glass. This additional adjustment is necessary because of the possible fluctuation of the volume of air trapped in the container, resulting from changes of absolute pressure or temperature in the system; but it can sometimes be omitted if the container is made very wide and very shallow. There is no need for these frequent zero settings in the type (I) gauge (Fig. 12): one setting here serves for a

series of readings. The single-column gauge (II), like its fellow the double-column gauge (Fig. 9 (I)), must be corrected for the weight of the air column of length h if the pressure exceeds permissible limits.

Example: The air pressure above the water columns in a differential gauge is 435 lbs./sq. in., and the metered liquid is water. What distance on the scale would represent 1 ft. head?

Density of air at 32° F. and 14.7 lbs./sq. in. is 0.0807 lb./cu. ft. Therefore density at (assumed) temperature of 60° F. and 435 lbs. gauge pressure

$$= 0.0807 \times \frac{435 + 14.7}{14.7} \times \frac{32 + 461}{60 + 461} = 2.34 \text{ lbs./cu. ft.}$$

From formula (5), § 15, $1 = h_2 \left(\frac{2.34}{62.4} - 1 \right) = -0.9625 h_2$, or
 $h_2 = 1.037 \text{ ft.} = \text{distance representing 1 ft. head of water.}$

(iii) In Fig. 12 (IIa) the type (II) gauge is shown in use as a steam-boiler water gauge. An ordinary water gauge (§ 12, Fig. 6 (I)) when fitted to the steam drum of a modern land boiler may be so far above the control floor that its indications are difficult to see, but the type (II) single-column gauge, when connected up suitably, may be brought to any desired position near the control point. Steam from the steam space of the steam drum passes to a small condensing chamber having an overflow weir adapted to keep a fixed water level, and from this reservoir a connection leads to the positive side of the gauge (Fig. 12 (IIa)). From the water space of the steam drum a connection leads to the negative side of the gauge. In this way the movement of the water column in the gauge tube almost exactly reproduces the movement of the column in a simple water gauge.

18. Inclined-tube Gauges. What seems to be an attractive way of increasing the sensitivity of glass-tube gauges is to set the gauge tubes in a sloping position, making a small angle with the horizontal, instead of setting them vertically. For a given change of head or differential head the movement of the indicating columns is thus greatly increased and the gauge can more accurately be read. The results of practically trying this improvement are apt to be disappointing, however, chiefly because of the difficulty of keeping a uniform meniscus

at the surface of separation of the two liquids—a problem which, even with vertical indicating columns, is often troublesome enough (§ 53). Unusual care is also necessary to avoid loss of the indicating liquid during venting and equalising (§ 54). It may therefore be wise to leave such gauges for the measurement only of air and gas pressures, in which field they can be used with confidence.

19. Methods of reading Glass-tube Gauges. Methods of varying degrees of refinement are available for observing the height of the indicating columns of glass-tube gauges, but in all of them it is the position of the horizontal plane tangential

to the meniscus that must be determined. If the gauge tubes are properly proportioned (§ 12) there should be no difficulty here, for the surface of separation should itself be plane except near the tube walls, and is not a true meniscus at all.

(i) For most engineering purposes it suffices to mount a graduated scale of paper, wood, or metal behind or by the side of the gauge tube (Figs. 6, 9, etc.). This can be read with an error that need not exceed 0.002 ft.

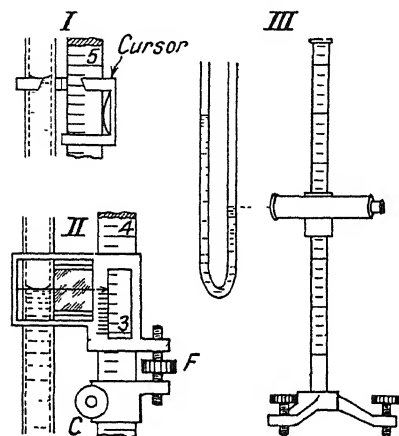


FIG. 13.—Precision devices for reading gauge tubes.

(ii) A metal cursor (Fig. 13 (I)), sliding on a metal scale, should reduce the limit of error to 0.001 ft. Such a cursor is shown in use in Fig. 12 (I).

(iii) The possible error may be brought within still narrower limits by using a cursor with hair-line, vernier, mirror for eliminating parallax, and slow-motion screw, as sketched in Fig. 13 (II).

(iv) Hook gauges as a means of defining the surface of separation have already been described (§ 16 (i)). If the apparatus is arranged as an inverted U-tube gauge with special indicating liquid, a practised observer would not expect an error of more than 0.0005 ft. when measuring differential heads.

(v) For experimental researches a cathetometer is a useful instrument (Fig. 13 (III)). The telescope can be moved up and down the vertical graduated column and can be trained on to either of the legs of a differential gauge; it can be accurately focussed on to the liquid surfaces, which are made to register in turn with the hair-line in the eyepiece. A limit of error of 0.0002 ft. ought reasonably to be expected.

20. Tilting Micromanometers. If none of the devices hitherto described are found suitable for measuring very small differential heads—which will only rarely happen—then some form of tilting micromanometer may be tried (Fig. 14). A glass U-tube having short, wide indicating columns spaced widely apart is mounted on a tilting frame supported at one

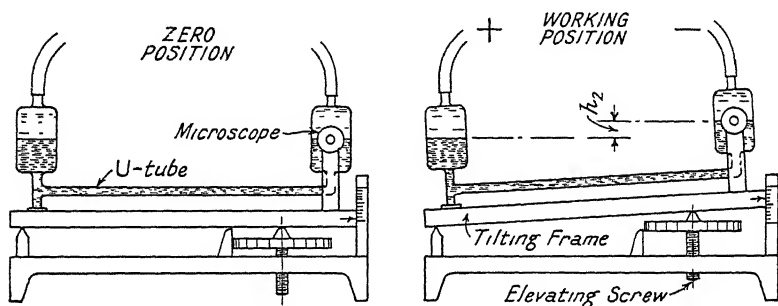


FIG. 14.—Tilting micromanometer.

end on knife-edges and at the other on the point of a micrometer elevating screw. The position of one of the surfaces of separation is observed by means of a microscope; its eyepiece has a horizontal hair-line, and its supporting bracket is attached rigidly to the tilting frame.

In the zero position, with zero differential head, the micrometer elevating screw is adjusted until the hair-line of the microscope exactly registers with the surface of separation in the leg of the U-tube; then, after the head to be measured has been applied, the elevating screw is turned to bring the hair-line again into registration. From the initial and final readings of the micrometer, together with the known dimensions of the apparatus, the deflection h_2 of the indicating columns, and thus the differential head, can be calculated (§ 15).

The Chattock micromanometer is a tilting gauge in which

a special construction of the U-tube permits still greater precision to be realised.⁽⁷⁾

It is worth remembering that such instruments were designed primarily for measuring air pressures, and that when measuring liquid pressures it is hardly justifiable to expect them to have the very minute errors—as low as 0·00001 ft.—that are sometimes claimed.

21. Limitations of Glass-tube Gauges. Glass-tube gauges are simple, often inexpensive, and they can be made to read accurately enough for nearly all purposes. But, on the other hand,

(i) The glass tubes are fragile, and often it is essential to replace a broken tube by one of exactly the same bore.

(ii) It may be unsafe to use glass tubes for high pressures.

(iii) Because of the possible change of density of the liquids used, the calibration of the gauge is valid only for specified metered and indicating liquids at specified temperatures (§ 52).

(iv) The indications of the gauge may sometimes depend on the exact amount of indicating liquid used.

(v) In their ordinary form the gauges cannot be made to operate an automatic recording mechanism giving a permanent record of pressure changes.

(For notes on the *installation and care* of glass-tube gauges, see Chapter III.)

GAUGES DEPENDING ON WEIGHING METHODS

The instruments classified under this heading differ from glass-tube gauges inasmuch as it is the *weight* rather than the *height* of liquid columns that is directly or indirectly measured; in all of them the fragile sight-glass is eliminated.

22. Methods of Weighing the Liquid Column. (i) The principle of weighing the liquid column is illustrated in Fig. 15 (I), which shows diagrammatically a steam-boiler water gauge.⁽⁸⁾ A vertical closed tube of cross-sectional area A communicates at top and bottom respectively with the steam and water spaces of the boiler drum, the connecting pipes being so long and flexible that they exert no constraint on small vertical movements of the indicating tube. A steelyard with jockey-weight W measures the weight of the tube and its contents,

this total weight $W \cdot \frac{L}{l}$ being directly related to the height h of the water column, for a given water density. To make the apparatus more suitable for general use, a spring balance can be substituted for the steelyard, as in Fig. 15 (Ia), the dial being graduated directly in units of water depth. But now the indicating tube no longer remains at the same level; it sinks by an amount δh under unit change of water level, and this must be taken into account in calibrating the gauge (compare § 11).

(ii) *Tilting U-tube.* If a U-tube is fitted with flexible connections and is balanced on a central knife-edge, it will tilt as

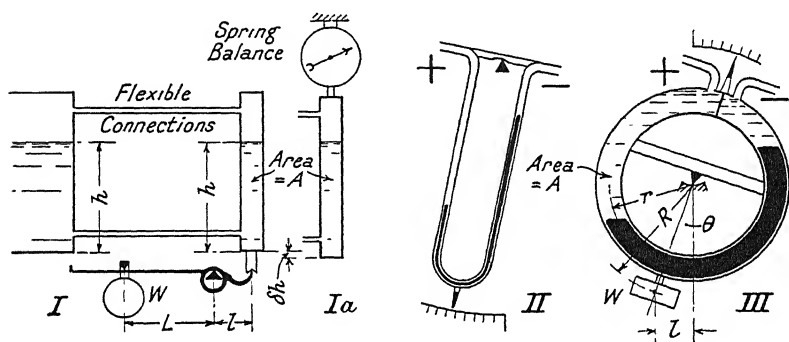


FIG. 15.—(I) Weighing the liquid column.
(II) Tilting U-tube
(III) Ring-balance meter.

the differential head is applied (Fig. 15 (II)), and a pointer moving over a circumferential scale can be made to indicate the head. A much more convenient form of this instrument is the ring balance.

23. Ring-balance Meter. This differential gauge has a U-tube bent accurately into a circle, of mean radius r (Fig. 15 (III)), the ring being balanced on a knife-edge at its axis. To resist the turning moment as the differential head is applied, a weight W acting at radius R is provided. The relation between the difference of pressure p and the angle of tilt θ is then obtained thus:—

The differential pressure acts on the radial partition or diaphragm, of area A , which divides the positive from the

negative compartment of the ring. Therefore, tilting moment $= pAr$. Now restoring moment $= Wl = WR \sin \theta$. Equating,

$$p = \frac{WR \sin \theta}{Ar},$$

which permits the circumferential scale to be calibrated.

It is most important to notice that neither the quantity nor the density of the indicating liquid enters into this equation: in fact the liquid is not an indicating liquid at all—it is a sealing liquid. This independence, which of course has great practical value, also follows from the fact that if the ring is accurately constructed no pressure on any of its surfaces can exert a torque: it is only the pressure on the *partition* that matters.

The ring-balance meter is another example of an instrument which, while widely used for gas measurement, has a limited field of application for liquid measurement. Here the angle of tilt must be kept small, otherwise difficulties arise in venting entrapped air from the compartments (§ 45).

A ring-balance meter adapted for flow measurement is described in § 216.

24. Precision Pressure-balance. For measuring differential pressures under laboratory conditions the apparatus sketched in Fig. 16 offers interesting possibilities.⁽⁹⁾ A light steelyard (in this instance a boxwood metre scale) is secured to the tilting frame carrying the mercury containers, and as the position of the jockey weight is always read when the beam is level, the possibility of varying reaction from the flexible connections can be ruled out. Assuming the containers to be accurately machined to a diameter d , then the differential pressure has the value

$$p = \frac{W(L - L_0)}{\frac{\pi d^2 l}{4}},$$

where L_0 is the zero reading of the jockey weight on the steelyard.

In a pressure balance designed for working under a pressure of 1000 atmospheres,⁽¹⁰⁾ the containers had a diameter d of 1.000 cms., the arms l were 10 cms. long, the flexible steel connecting tubes were 100 cms. long and 2 mm. outside dia-

meter, attached close to and parallel with the axis, and the differential torque was measured not by a steelyard but by weights on a scale pan, as in a chemical balance. The maximum error when the balance was calibrated against a water-column gauge was stated to be 0.3 per cent.

As in the ring-balance meter, the liquid here used is a sealing liquid only whose physical characteristics have no influence on the calibration. But in designing the containers the density of the liquid must be approximately known so that the deflection (§ 15) may be calculated and the height of the containers adapted to the working range of pressures.

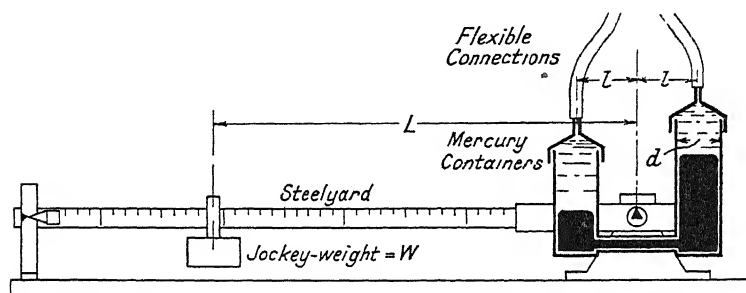


FIG. 16 — Precision pressure-balance.

DEAD-WEIGHT GAUGES

25. Primary and Secondary Standards of Measurements. In principle all the gauges described in the previous sections could be regarded as primary standards because their indications depend only on observations of length, weight, or time. As already pointed out, there is frequently the important reservation concerning temperature effects to be kept in mind; but since this does not apply to some of the gauges, e.g. the pressure balance, these are true primary standards. On the other hand, gauges depending on the elastic deformation of metal elements (§§ 27-29) are certainly secondary standards, for they can only be calibrated by comparing them with some primary standard gauge. The most reliable form of standard pressure gauge is the dead-weight gauge.

26. Dead-weight Gauges. A typical gauge testing outfit is sketched in Fig. 17 (I). The standard gauge consists of a

very accurately-machined steel plunger working in a cylinder containing oil: in parallel with this gauge is the dial or other gauge under test. A small hand-pump forces oil under the same pressure to both gauges, and the pump is worked until the plunger and the weights which load it begin to float freely. Frictional lag is eliminated by rotating the plunger by hand. Then the pressure is represented by the value

$$p = \frac{\text{total load on plunger}}{\text{cross-section of plunger}}.$$

By adding more weights, other pressures are applied, and thus the calibration of the dial gauge can be completed.

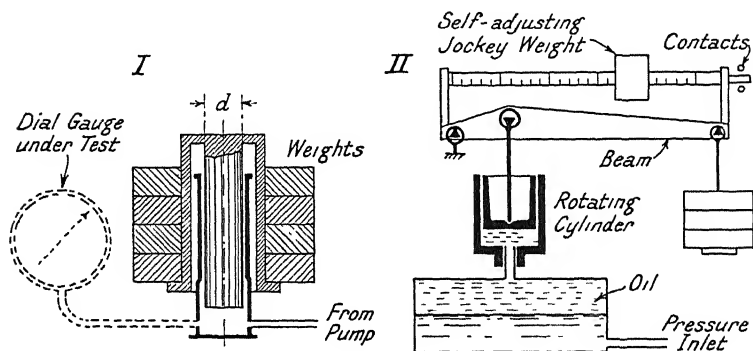


FIG. 17.—Dead-weight gauges.

Only when the pressure to be measured is very great, and the diameter of the plunger is correspondingly small, is there any uncertainty in determining p . In such cases the clearance between the plunger and its cylinder is no longer negligibly small, and thus, instead of using the diameter d of the plunger in calculating its area, the mean of the plunger diameter and the cylinder diameter must be taken.

The normal pattern of dead-weight gauge (I) can only deal with fixed increments of pressure, but a modification suitable for measuring any pressure throughout a given range has recently been developed.⁽¹¹⁾ Fig. 17 (II), which is purely symbolical, shows that the plunger is loaded by weights hung from the end of a beam and also by a smaller jockey weight that can be traversed along the beam. The main suspended weights having been set to suit the expected pressure, the

jockey weight is automatically traversed in or out along the beam to maintain equilibrium. A small electric motor looks after this duty, an upper and lower contact switching it into or out of service when the beam tilts under changes of pressure. Thus the position of the jockey weight, together with the number of main weights, gives an indication of the pressure. Another electric motor slowly rotates the cylinder so that friction cannot have any sensible effect on the motion of the plunger, and a large container beneath serves to transmit to the oil system the pressure of the water under test. Although an extremely costly apparatus, its accuracy under engineering

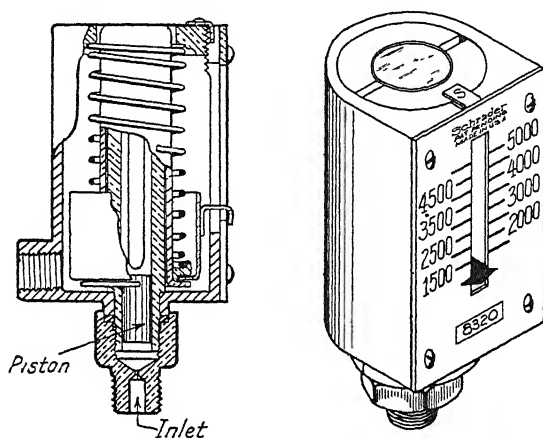


FIG. 18.—Spring-loaded piston gauge.

conditions is unrivalled: it is claimed that the gauge is sensitive to a change of 0.01 lb./sq. in. through a range of 0-550 lb./sq. in.

GAUGES DEPENDING UPON THE ELASTIC DEFORMATION OF METALLIC ELEMENTS

27. Spring-loaded Piston Gauges. Substituting a helical metallic spring for the weights of the dead-weight gauge results in a simple, compact, and portable instrument which gives a direct reading of the pressure. The construction is seen from Fig. 18, which shows a gauge made by the A. Schrader Co.; the pressure is applied to a small piston working in a cylinder, and is indicated by a pointer moving over a linear scale. Such

gauges are useful when violently-fluctuating pressures are found, as in industrial hydraulic press work. Here accuracy is willingly sacrificed to strength.

If the travel of the piston is not too great, the inevitable slight leakage between cylinder and piston may be prevented by stretching an impermeable flexible membrane over the head of the piston.⁽¹²⁾

The steam- or gas-engine indicator is another example of a spring-loaded piston gauge; such instruments are sometimes required for hydraulic work, e.g. in taking indicator diagrams of the pressure in reciprocating pumps. Suitably modified, they are quite useful in experimental researches, e.g. investigating water-hammer or pressure fluctuations in pipe-lines.

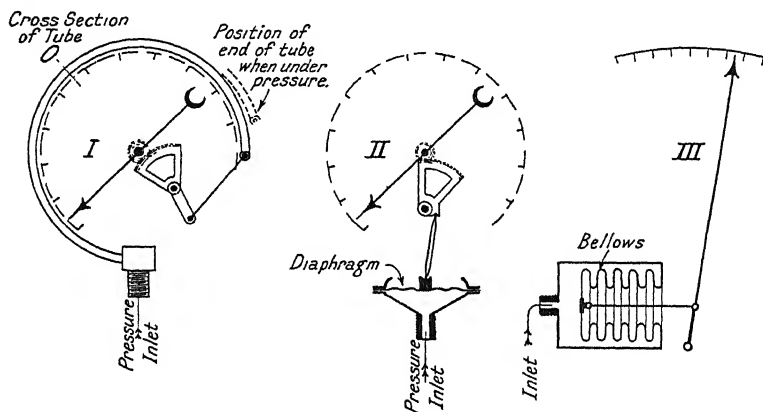


FIG. 19.—Elastic elements for pressure gauges.

28. Other Pressure-responsive Systems.

(i) *The Bourdon tube.* The tube is of bronze or steel, depending upon the pressure, usually of elliptical cross-section, and it is curved into a circular arc (Fig. 19 (I)). When pressure is applied the tube tends to straighten, its closed end moves slightly outwards, and the movement is transmitted through a link, quadrant, and pinion to a pointer working over a circumferential scale. The necessary magnification can also be achieved by coiling the tube into a spiral or into a helix.

(ii) *The diaphragm.* In Fig. 19 (II) an elastic steel corrugated diaphragm is used for operating the pointer. A pair of diaphragms joined together to form a closed chamber is called

a capsule, and a number of capsules may be coupled together when a longer travel is wanted than a single diaphragm would give. This system, used, for example, in the recording barometer, is generally more suited for gases than for liquids.

(iii) *The bellows.* This element (III) is formed of a thin metallic tube having deep circumferential corrugations: it expands or contracts, concertina fashion, under the influence of pressure changes, the movements being indicated on a suitable scale.

29. Characteristics of Elastic Elements. One of the chief virtues of the pressure-measuring elements shown in Fig. 19 is that they are suitable for the entire range of pressures encountered in normal engineering practice—say from 1 to 10,000 lbs./sq. in.; they can equally well measure suction or negative pressures. Instruments calibrated for both positive and negative pressure are termed *compound gauges*. To adapt the gauge for any desired maximum pressure it is just a matter of correctly proportioning the wall thickness, etc., of the element, and of designing appropriate multiplying gear. The instruments are portable and compact, they have an open, easily read scale, and consequently for high pressures at least they are the only kind suitable for industrial use. They can readily be built as *self-recording gauges*, in which a pen is substituted for the pointer, moving over a paper chart rotated by clockwork (Fig. 20).

As already explained (§ 25) the gauges can only be calibrated against a standard gauge—usually a dead-weight gauge. Compared with liquid-column gauges their accuracy is not very high: if one were to test a number of dial gauges having elastic elements, in normal use in any industrial establishment, probably few of them would have an error of less than 1 per cent. of the full-scale reading. The errors are partly to be

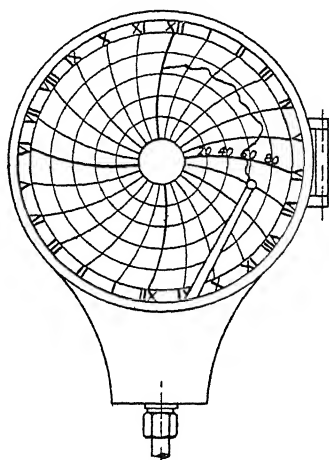


FIG. 20 —Recording pressure-gauge.

attributed to a permanent set of the element caused by subjecting it continually to large deflections ; for this reason dial gauges should preferably not be allowed to work for long periods at the maximum pressure shown in the scale. Nor should very hot liquids be allowed to enter the gauge. The Bourdon tube and the bellows have the advantage over the diaphragm that their response is nearly linear—that is, equal increments of pressure produce equal deflections throughout the whole useful range of movement.⁽¹²⁾

The production of satisfactory *differential* gauges using elastic elements is not easy : although a combination of two bellows working *vis-à-vis* looks attractive, one having a positive and one a negative connection, it is found in practice to be sluggish in its response to changes of differential pressure. In experimental work a Bourdon helix element enclosed in a chamber and working an optical indicating system has been used for measuring differential heads.⁽¹³⁾

CHAPTER II

INDIRECT INDICATION AND TRANSMISSION OF PRESSURE, HEAD, OR DEPTH READINGS

	§ No.		§ No.
Types of indicating and trans-		The Selsyn system . . .	37
mission systems . . .	30	Variable-current systems . . .	38
Diaphragm - type pneumatic		Ratiometer systems . . .	39
gauge . . .	31, 32	Audible electric systems . . .	40
"Bubble"-type pneumatic gauge	33	High - frequency, variable - re-	
Electrically - indicating point		sistance devices . . .	41
gauges, etc. . .	34, 35	Piezo - electric pressure indica-	
Step-by-step system . . .	36	tors . . .	42

30. Types of Auxiliary Transmission Systems. The fact that the appliances described in Chapter I are nominally direct-reading does not necessarily imply that the observer must station himself immediately by the side of the tank or pipe in which pressure or depth measurements are to be made. Float gauges, for example, can give their indications many feet above the water surface whose level they register, and if need be pressure gauges may be set fifty or a hundred feet away from the gauge point to which they are connected. But for many purposes it is desirable and sometimes essential to be able to transmit information over far greater distances than these, the need for such systems being bound up with the increased use of remotely controlled apparatus and with the desire to group at some central control station a complete set of indicating and recording instruments.

Pneumatic systems of various forms are highly satisfactory for distances up to several hundred yards, while *electric* systems will operate over scores of miles. It is often very convenient also to use electrical auxiliary appliances for indicating as well as for distant transmission. In a book of this kind only a few of the simpler electrical systems can be mentioned.

Hydraulic transmission occasionally has advantages, using the term to denote systems having a relatively high-pressure

circuit wholly distinct from that of the metered liquid. An example is shown in Fig. 21, where a distant pointer indicates liquid level in a container.⁽¹⁴⁾ Opposed bellows are used both as transmitter and receiver, and as the twin tubes are laid side by side, temperature and pressure changes have no effect; moreover, the whole hydraulic system is hermetically sealed. The large operating force available removes the possible objection to opposed bellows mentioned in § 29.

In a somewhat similar way the variations in the buoyancy of a displacer (§ 11) may be translated into pressure variations and transmitted along a thin hydraulic tube to a pressure gauge graduated in units of depth.

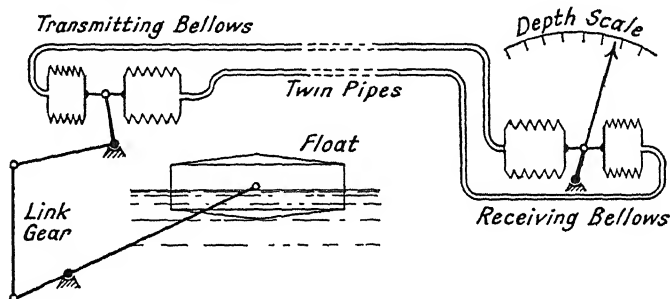


FIG. 21.—Hydraulic transmission system.

PNEUMATIC TRANSMISSION SYSTEMS

31. Diaphragm-type Pneumatic Gauges. These gauges convert the liquid pressure to be measured into air pressure, which is transmitted through a small-bore flexible tube to a pressure gauge graduated in units of pressure, depth, or level as required. An example designed for measuring liquid level in an open vessel is illustrated in Fig. 22 (I). A metal bell or diaphragm box is hung from a chain near the bottom of the vessel, the mouth of the bell being closed by a thin, flexible india-rubber diaphragm; this diaphragm is of such construction that it imposes no restraint at all on the liquid in contact with it, and consequently the air pressure above it, viz. the air pressure indicated by the gauge, is precisely equal to the static pressure corresponding to the liquid head h . As the liquid level changes, so does the air pressure and so does the gauge reading.

The system has the important practical advantage that as the liquid to be measured never enters the bell or connecting pipe, all kinds of thick, dirty, or corrosive liquids can be gauged. The length of the thin connecting pipe or capillary tube may be 100 ft. or more, but it is absolutely essential that all joints in the air system are hermetically tight. A recording gauge (Fig. 20) can perfectly well be substituted for the indicating element, any of the pressure-responsive systems shown in Fig. 19, § 28, being suitable.

By modifying the construction slightly the diaphragm gauge can be adapted for measuring the depth of rivers.⁽¹⁵⁾ Another variant uses a "flabby" metallic diaphragm in place of an india-rubber one.⁽¹⁶⁾

32. Corrections to Pneumatic Gauge Readings. The fixed weight of air sealed within the bell, the capillary tube, and the indicating element must certainly undergo changes of volume whenever its pressure or its temperature alters; and it is necessary to see whether the corrections thereby required are negligibly small or not.

(i) *Temperature.* Suppose that the total weight of air is equal to that contained in a cylindrical bell in which the cross-section is A (Fig. 22 (II)). Then let

d = vertical height of air space when absolute temperature is T and head of liquid, of density w , is h .

δd = vertical distance through which liquid surface in the bell is depressed when the air temperature rises from T to T_1 , the liquid surface level remaining unaltered.

h_a = atmospheric pressure expressed as head of liquid.

The initial and final volumes of the air are evidently Ad and $A(d + \delta d)$ respectively, and the corresponding initial and

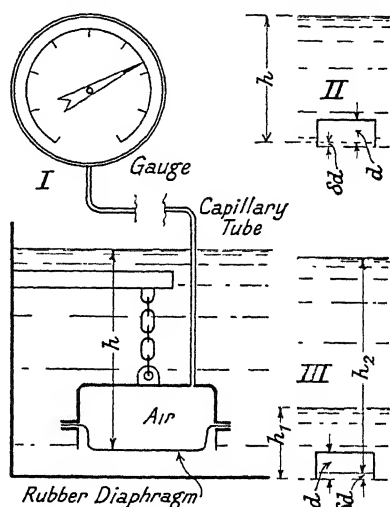


FIG. 22.—Diaphragm-type pneumatic gauge.

final absolute pressures P and P_1 are $w(h + h_a)$ and $w(h + \delta d + h_a)$. These quantities are connected by the equation of state :

$$\frac{PV}{T} = \frac{P_1 V_1}{T_1},$$

from which
$$\frac{(h + h_a)d}{T} = \frac{(h + \delta d + h_a)(d + \delta d)}{T_1}.$$

The value δd can thus be found.

Example : If $T = 521$ (60° F.), $T_1 = 561$ (100° F.), $d = 0.5$ ft.,
 $h = 5$ ft., $h_a = 34$ ft.,

then $\delta d = 0.038$ ft.

In other words, the temperature rise of 40° F. would cause the gauge reading to increase by 0.7 per cent. *without any change in liquid level.*

Although this error is hardly more than might be expected in the indicating mechanism itself, it is sufficiently high to suggest the need for keeping the air volume in the system as small as possible. On the other hand, the effect of change in air volume under temperature changes might be wholly or partly compensated by variations in the density of the liquid created by the same temperature changes.

(ii) *Pressure.* Suppose that in Fig. 22 (III) the equivalent depth of air in the bell is d when the head of liquid is h_1 , and that the air depth is $(d - \delta d)$ when the head is h_2 , the amount δd representing the diminution in volume of the air as the pressure acting on it increases. Then if h_a is the head of liquid corresponding to atmospheric pressure, and if the temperature remains unaltered, we have

$$PV = P_1 V_1, \text{ or } (h_1 + h_a)d = (h_2 + h_a)(d - \delta d).$$

Example : Let

$$\begin{aligned} h_1 &= 1 \text{ ft.} \\ h_2 &= 20 \text{ ft.} \\ h_a &= 34 \text{ ft.} \\ d &= 0.5 \text{ ft.} \end{aligned}$$

Then from the above expression δd is found to be 0.18 ft. ; that is, while the indicator has shown an increase of head of 19 ft., the actual change of level has been $19 + 0.18$ or 19.18 ft. This difference, however, can be taken care of when calibrating the gauge.

33. "Bubble"-type Pneumatic Gauge. In this system the air is in direct contact with the liquid (Fig. 23 (I)), and the

liquid level in the bell is kept at a fixed height when taking readings by allowing air to bubble through a slot in the side of the bell or beneath the bottom of the bell. A single-column mercury manometer measures the air pressure, and a hand air-pump forces into the bell the necessary excess air. Usually a change-over cock is fitted so that the bell can be put into communication first with the pump and then with the manometer. There are no corrections to be made; after the excess air has bubbled away, the pressure indicated by the gauge is truly the pressure corresponding to the head h . Thus the system is the most reliable of all distant-reading systems, but its applicability is limited by the cost of the piping between the manometer and the bell; this usually becomes prohibitive if the distance between them is more than 1000 ft.

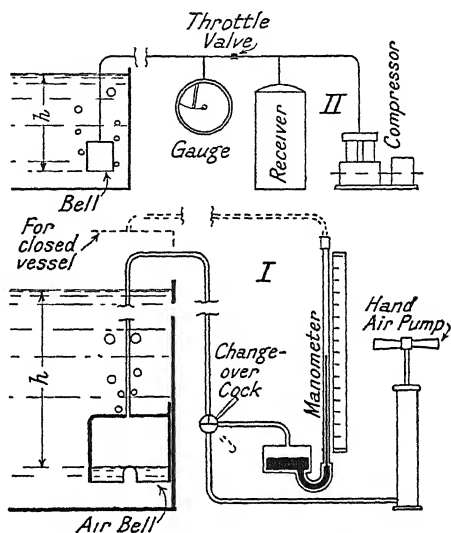


FIG. 23 —“Bubble”-type pneumatic gauges.

In calibrating the manometer scale the formula

$$h = h_2 \left(1 + \frac{a}{A} \right) \frac{w_1}{w} \quad . \quad . \quad . \quad (7)$$

should be used, in which the symbols are those of equation (3), § 13 (ii). The sensitiveness of the manometer can be increased if desired by making it of similar form to the one described in § 14, Fig. 8 (II), an indicating column of oil floating on the mercury in the U-tube. Liquid levels in closed vessels can be read by making the modification shown in broken lines (Fig. 23 (I)).

To adapt the bubble gauge to continuously-recording indicators the arrangement of Fig. 23 (II) may be used. An air receiver periodically charged by a small motor-driven

compressor delivers a continuous stream of air through a needle regulating valve and so to the bell, the recording pressure gauge

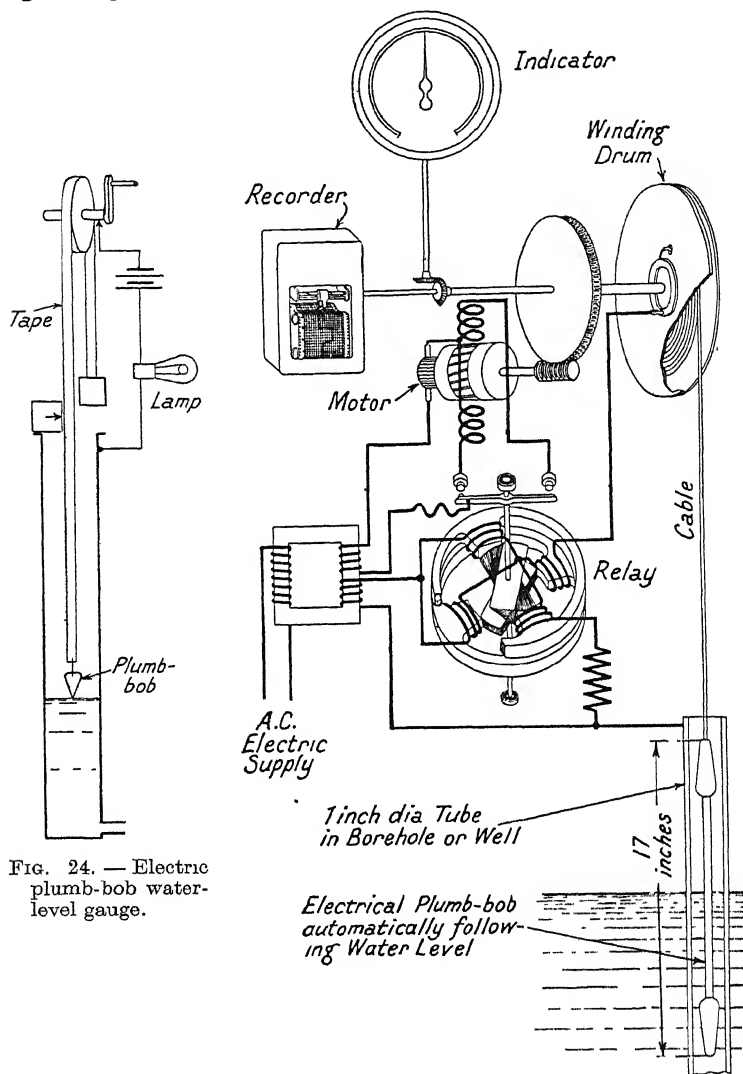


FIG. 24. — Electric plumb-bob water-level gauge.

FIG. 25.—Automatic electrical plumb-bob for bore-holes.

communicating with the pipe line downstream of the valve. The air friction between the gauge and the bell tends to make

the gauge read high, but if necessary this difficulty could be overcome by running a separate return lead direct from the bell to the gauge.

Because of its simplicity, robustness, and, in one form at least, great accuracy, the "bubble" gauging system is very widely used both on land and sea for indicating the depth and volume of liquids of various sorts—especially oils—in storage tanks and vessels.

ELECTRICAL INDICATING AND TRANSMITTING SYSTEMS

34. Point Gauges, Plumb-bob Gauges, etc. The simplest application of electrical indicating methods is found in a point gauge (§ 8) having a platinum tip which completes an electric circuit as soon as the point touches the water surface. The circuit includes a telephone or a buzzer which gives the signal to the observer. The system is very convenient when the water surface is at the bottom of a deep gauge well where visual observation would be difficult. A similar arrangement comprising a graduated metal tape wound on a reel, a plumb-bob, and a signal lamp ⁽¹⁷⁾ is sketched in Fig. 24, and portable outfits are available for measuring the head over weirs, etc. ⁽¹⁸⁾ In any of these systems the errors of measurement need hardly be greater than with a direct-reading point gauge; in none of them should the voltage of the battery which gives the signal current exceed about 4 volts.

A much more elaborate arrangement devised by Evershed & Vignoles, Ltd., for automatically recording the depth of water in bore-holes is shown in Fig. 25. Here a 50-volt electric motor drives the reel or winding drum on which is wound the cable corresponding to the metal tape of Fig. 24; the plumb-bob is an electrical element which automatically follows the water level, being electrically coupled to the relay so that the motor winds in or pays out the cable as required. Mechanical gearing enables the indicator and the recorder to show the water level, correct to within a few inches, over a range of 400 ft.

35. Multiple Point-gauge Systems. If instead of using a movable point gauge a number of fixed gauges with electrical contacts were set at various heights, the rise of the liquid in the vessel could be detected by the successive signals given.

Fig. 26 suggests a development of this proposal: a number of insulated conductors of varying lengths project downwards into the liquid, their upper ends being interconnected by suitably

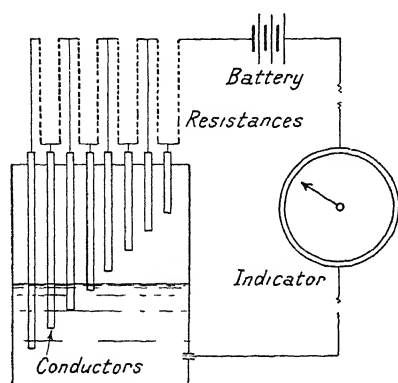


FIG. 26.—Electric multiple-point gauge

conductors that would be needed to cover a useful range of liquid level, the system in its primitive form is not often used, but when modified for measuring differential heads (§ 225) the principle has commercial utility.

graded resistances which form part of a circuit including a battery and an ammeter or galvanometer. As the liquid level changes, resistances are cut out of circuit or put into circuit again, the current flowing in the circuit varies accordingly, and thus by suitable calibration the ammeter could be made to show liquid level or depth. Because of the multiplicity of

ELECTRO-MECHANICAL TRANSMISSION SYSTEMS

This title is here given to those transmission systems in which the hydraulic and the electric circuits are kept wholly separate—unlike the systems just described. Changes in liquid level or pressure originate a mechanical movement, e.g. the rise or fall of a float, and electrical means are only provided to transmit this movement to the distant station. The transmitting element may thus be in the nature of a float or the like arranged to modify an electric circuit, and the receiving element may be an instrument in the nature of an ammeter graduated in units of depth or pressure.

36. Step-by-step System. As Fig. 27 shows, the rise or fall of the float in this system causes a star-wheel to revolve and thus, by closing the circuit each time a tooth raises the contact arm, to send an impulse along the transmission line. Each impulse energises an electro-magnet at the receiving station and causes a ratchet-wheel there to advance by one tooth, and in this

way a pointer on the ratchet-wheel spindle, or geared to it, can show the liquid level. Another electro-magnet (not shown in the diagram) takes care of rising movements of the float. The interesting mechanical problems that arise in the design of the transmitter—for instance, to ensure that a short, defined electrical impulse is given no matter how slowly the float moves—can be solved without undue difficulty. The construction throughout can be simple and substantial; the system is suitable either for D.C. or A.C. operation, using either one or two line-wires; and apart from actual failure of the current the indicator is bound to keep accurately in step with the transmitter. Consequently, this system is frequently chosen for sending to stations ten or twenty miles away the indications of water levels in storage reservoirs.

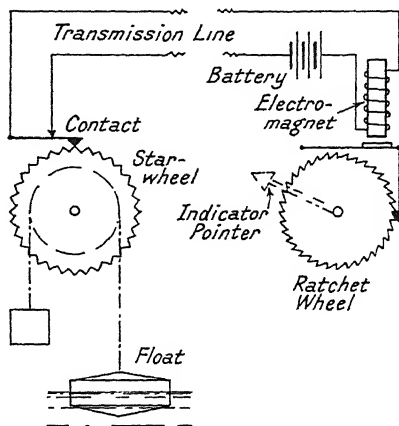


FIG. 27.—Step-by-step transmission system

37. The Selsyn System. This has a certain similarity to the step-by-step principle inasmuch as a revolving element at the receiving end is constrained to reproduce the movements of an element at the transmitting end which is mechanically driven by some hydraulically-operated device. The arrangement illustrated in Fig. 28 is used by Messrs. Guest & Chrimes to give remote indications of the differential head and thus of the discharge of a Venturi meter, the secondary element of which is of the type shown in Fig. 133 (III), § 215; it is the float-operated pinion which is geared to the rotor of the Selsyn transmitter. The electrical components of receiver and transmitter are identical; each has a rotor connected by slip-rings to a single-phase supply network, and a stator having three-phase windings, the corresponding windings being connected by three line-wires. The system thus has, to some extent, the characteristics of an A.C. generator and synchronous motor,

an increase of torque creating an increased angle of lag between the receiving and the transmitting rotor. But as a very small torque is needed to drive the indicating or recording mechanism, the lag need have a negligible effect on the accuracy of transmission.

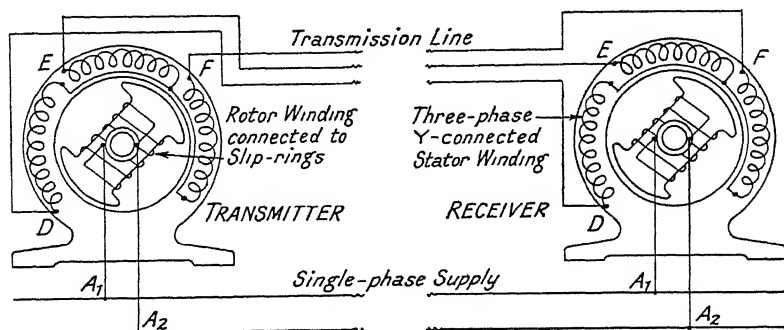


FIG. 28.—Selsyn system.

38. Variable-current Systems. Here we arrive at layouts which actually are examples of the principle outlined in the introduction to this section—the A.C. current in the transmission line is continuously controlled at the transmitting end, and the receiver is in the form of an ammeter or voltmeter.

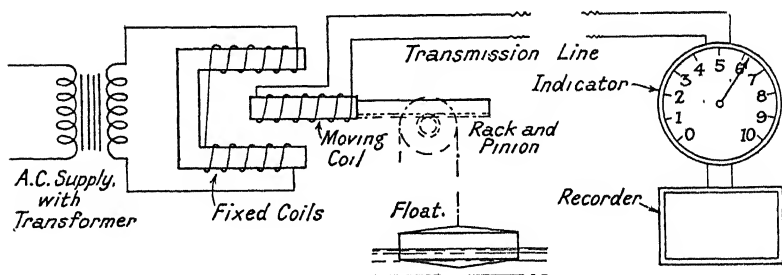


FIG. 29.—Variable-current system (Gent & Co.)

Messrs. Gent & Co. use a coil, operated by float, rack and pinion (Fig. 29), which moves longitudinally between two fixed coils energised through a transformer from a standard A.C. supply. The variable current induced in the moving coil is rectified at the receiving instrument and fed to a suitably graduated indicating or recording voltmeter.

Messrs. Elliott Bros. also use a constant voltage coil T_5 (Fig. 30) fed from the supply mains, and a coil T_6 in which the strength of the induced current is modified by a moving element operated by a float, pressure-gauge, or the like. Here the moving element is a coupling loop t ; it passes on the one side between the narrow air-gap of the exciting field system T_5 and on the other side between the corresponding air-gap of the output field system T_6 . By appropriately controlling the shape of the coupling loop t , the transmission system can be given any desired characteristic—that is, there may be any desired relationship (within limits) between the angle of twist imposed on the loop spindle and the induced current that is rectified and transmitted to the indicating or recording ammeter.

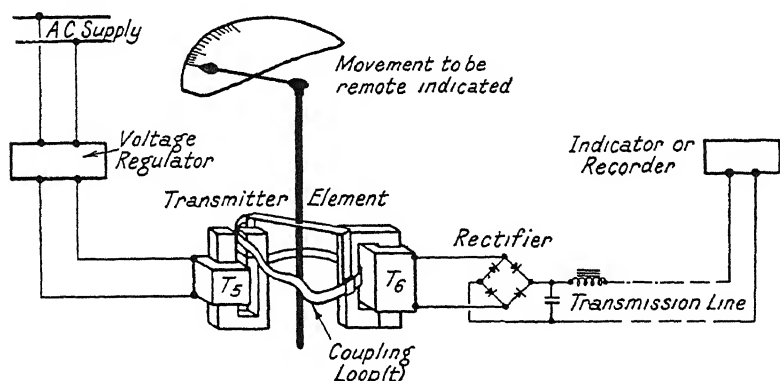


FIG 30—Variable-current system. (Elliott Bros.)

39. Ratiometer Systems. Here the duty of the transmitter is not to alter the current strength but to vary the ratio between two currents or two electrical pressures; it is the varying influence of these two currents which, acting on the moving element of the receiver, causes its pointer or pen to take up its appropriate position on the scale of levels, pressure, etc. Although three-line wires are now needed instead of two, there is no longer the necessity to insist on a constant supply voltage. Fig. 31 shows the elements of the system developed by Messrs. Evershed & Vignoles, Ltd. A copper sleeve at the transmitting end is caused by a float to travel axially over two iron-cored coils connected across the A.C. supply lines; when the sleeve is in its mid-position the inductances of the two coils are equal,

but when it is moved to an unsymmetrical position the inductances are no longer equal. In this way the ratio of the currents in the two coils of the receiving instrument—a rectifier type ratiometer—is varied, and the indicating element moved accordingly.

Another system employs a potentiometer type of transmitter,⁽¹⁹⁾ the float causing a brush to move over a coiled resistance.

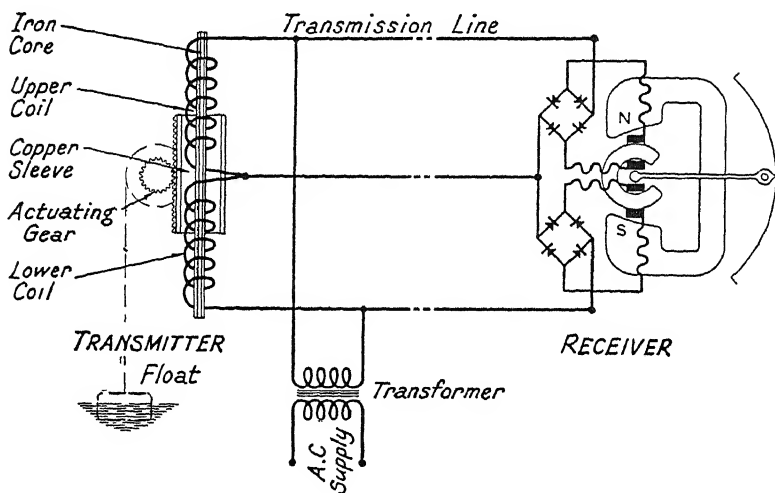


FIG. 31 —Ratiometer system.

40. Audible Transmission Systems. One of the most costly items in an ordinary electrical transmission system is the installation or the hire of the transmission line itself, no matter whether this is a private telephone circuit or a special line. In order to minimise this expense and to enable as far as possible the Post Office telephone system to be used instead, Messrs Gent & Co. have devised an audible level-indicating system. The installation at the reservoir whose levels are to be transmitted is connected to the public telephone system and given a number as though it were a normal subscriber's installation. To use it, the engineer puts through a call to this number from any other telephone instrument in his own office or elsewhere, and listens: he will then hear a number of signals or pulses, which he counts, one signal for each foot of water on the scale of reservoir levels, and then a further series of signals, of

distinctive tone, indicating the additional number of inches. The equipment is quite simple and reliable ; an arrangement of rotary contacts operated by the reservoir floats, connected to stepper switches, with the necessary relays, are its main elements.

Audible automatic transmitting instruments embodying gramophone records have also been tried which, when called up from the engineer's telephone, announce the water level in feet and inches much as the " talking clock " tells the subscriber the time.

Good results have been reported ⁽²⁰⁾ from automatic radio transmitters working on a wave-length of 116 metres and having a range of 100 miles.

HIGH-FREQUENCY ELECTRICAL INDICATING SYSTEMS

In general these are required purely for experimental work, as, for example, in measuring very rapid pressure changes such as occur in wave impact, compression-ignition engine fuel-pumps, and so on.

41. Variable-resistance Devices. The change in resistance that carbon undergoes when subjected to variations of mechanical pressure has been successfully applied to the measurement of very rapidly fluctuating hydraulic pressures. In the type known as the Carbon Resistor Type Telemeter ⁽²¹⁾ a number of annular rings of hard carbon about 7/16 in. diameter and 0.02 in. thick are mounted in a pile or stack, provided with copper contacts, and enclosed in a liquid-tight casing of which one face or end receives the liquid pressure to be measured. The elastic deformation of the casing is arranged to vary the pressure on the carbon pile, and the resulting changes in electrical resistance can be measured by a Wheatstone bridge or utilised to operate an oscillograph. Calibration is carried out by subjecting the instrument to known static pressures, which may be as high as 20,000 lbs./sq. in.

Pressure fluctuations in small pipes have been measured by observing the elastic yield of the pipes themselves when under pressure ⁽²²⁾ ; the expansion of the pipe was caused to compress two pieces of graphite (lead from writing pencils), and the fluctuations in electrical resistance were indicated by a thread galvanometer.

42. Piezo-electric and other Pressure Indicators.

The piezo-electric effect, by which quartz crystals become electrically charged at the free surface when subjected to mechanical stress, is now being extensively used for research in high-frequency pressure changes.⁽²³⁾ The crystals used in recent wave-pressure investigations⁽²⁴⁾ were contained in a stainless-steel capsule $\frac{3}{4}$ in. diameter mounted in a heavy brass plug. The liquid pressure exerted on the end of the capsule, when transmitted to the two crystals, produced an extremely minute electric charge which was conveyed to a 2-valve amplifier and then further amplified before being fed to a cathode ray oscillograph.

Another method of measurement depends upon changes of electrical capacity when one metallic diaphragm is moved relatively to another, the two constituting a condenser.⁽²⁵⁾ One of the diaphragms, which need only be 2 or 3 mm. diameter, deflects elastically when liquid pressure is applied to it, and from the corresponding measured electrical changes the value of the liquid pressure can be determined.

CHAPTER III

INSTALLATION AND OPERATION OF PRESSURE AND DEPTH GAUGES

	§ No.		§ No.
Tappings at gauge point . . .	43	Care and maintenance of gauges . . .	50
Connecting pipes . . .	44, 45	Indicating liquids . . .	51, 52
Connections for dirty and viscous liquids . . .	46	Calibration of glass-tube gauges . . .	53
Damping methods . . .	47, 48, 49	Overload devices . . .	54

LIQUID pressure and level gauges are unusually sensitive to the manner in which they are connected up. In discussing some of the numerous important matters that must be attended to, the system here chosen is to begin at the gauge point and to follow the connections along to the gauge itself.

43. Tappings at the Gauge Point. In order to measure the pressure or depth in a pipe or vessel at a given point—called the gauge point—it is usually necessary to make an opening in the wall of the pipe or vessel for the reception of the connecting pipe leading to the gauge. If the liquid is at rest or virtually at rest, as in a tank, cistern, or reservoir, special precautions are rarely necessary, beyond taking care that the opening cannot be choked by dirt, rust, etc. But if the liquid is flowing past the opening, then the siting and the making of this pressure tapping must be very carefully watched if appreciable errors are to be avoided.⁽²⁶⁾

(i) The gauge point must be chosen in a *straight length of pipe*, because pressures measured at the outside of a curved pipe will be greater than the mean pressure, and at the inside will be less than the mean pressure (§ 128). As an additional precaution in truly obtaining the mean pressure, a number of equally-spaced tappings may be drilled at the desired plane perpendicular to the axis of the straight pipe, these communicating with a circumferential manifold or belt to which the gauge connection is made (§ 122, Fig. 81). If a single

tapping is thought adequate, it may be drilled on the horizontal diameter of the pipe, i.e. level with the pipe axis.

(ii) The tapping must be truly perpendicular to the pipe wall; any inclination of the opening, either towards or away from the current, may cause false gauge readings.

(iii) The opening in the pipe wall must have no surrounding irregularities likely to cause eddies; burrs caused by drilling must be removed, and if possible the inside of the hole in contact with the liquid should be lightly countersunk. If the pipe wall is so thin that the connecting pipe is screwed completely through it, the inner end must be finished off exactly flush: recessed or projecting ends, as at (I) and (II) in Fig. 32, are inadmissible. The type of tapping (III) is preferable, provided that the parallel part of the opening in the pipe wall is

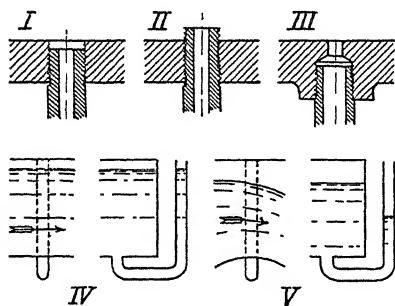


FIG. 32.—Incorrect and correct tapplings

diameter that will not get choked and that will not impose excessive damping (§ 47): this is of special importance when the pressure varies very rapidly along the pipe, as it does near orifice meters (§ 120, Fig. 83). Actually $\frac{3}{32}$ in. is as small as can usually be recommended. Perhaps $\frac{1}{8}$ in. is a good size for pipes up to 1 ft. diameter, and $\frac{1}{4}$ in. for larger pipes.

(v) In general the same precautions are needed for open channels as for closed pipes. When water flows horizontally along a channel having a virtually horizontal bed, the piezometric depth (the depth as measured by an open-column manometer) will accurately agree with the depth as measured by a point gauge (Fig. 32 (IV)); but should the channel bed be curved convex upwards, then the resulting vortex flow will

at least two diameters long. If possible the surface of cast-iron pipes should be brushed or scraped occasionally to remove rust and deposit from the neighbourhood of the tapping, while steel pipes may be galvanised to delay corrosion in this area.

(iv) Ideally the hole should be of the smallest

make the piezometer show a *smaller* depth than the true depth (Fig. 32 (V)).

44. Connecting Pipes between Gauge Point and Gauge. Theoretically there is no limit to the distance between the gauge point, where a knowledge of the pressure or liquid level is desired, and the gauge itself where the actual indications are given. Nor is it possible to lay down precise limits to the stages at which in practice it becomes desirable to abandon liquid transmission of pressure in favour of pneumatic systems, or again in favour of electrical systems (Chap. II). One can only point out that for a given distance the necessary electrical conductors are cheaper and easier to lay than an air pipe, and that an air pipe is less troublesome than a water pipe. In the same spirit it might be suggested that if the liquid transmission pipes are much more than 100 ft. long, then the difficulties arising from inertia surging, sluggish operation, air-locks, etc., might become serious.

In regard to the vertical distance h_0 between the gauge point and the gauge, this will have no effect on the readings so long as the graduations are correspondingly adjusted, in such a way that the gauge reads zero when the pressure at the gauge point is zero. But if this is impracticable, e.g. if a dial pressure gauge is used which always indicates the pressure at the gauge itself, then the reading must be corrected by an amount wh_0 . This correction must be subtracted from the reading if the gauge is below the gauge point, and added if the gauge is above the gauge point. It is for this reason that the temperature of the column of metered liquid in the vertical lengths of the connecting pipe cannot always be ignored; temperature changes here may result in changes of density which in turn affect the value of the term wh_0 . To avoid the need for any such corrections when differential gauges are concerned, the twin connecting pipes should always be laid side by side.

When *negative* (i.e. vacuum or suction) pressures or heads are to be measured it is in every way advantageous to keep the connecting pipe as short as possible. In this way the risk of air leaks is minimised (§ 45). If the gauge can be directly coupled to the gauge point, so much the better.

The *diameter* of the pipe connections may vary from $\frac{1}{4}$ in.

to 1 in., depending on the viscosity of the liquid and on the transmission distance. It never does any harm to err on the generous side when fixing the size. All joints should be dead tight.

45. Air in Connecting Pipes. Only on one condition is it true to say that in general the length of the connecting pipes has no influence on the gauge readings, and the condition is that the pipes should be *completely full of the metered liquid*. If at any point the continuity of the liquid column in the pipe is broken by air or gas bubbles, then the gauge readings may be rendered wholly worthless. Air may get into the connecting pipes in three ways: (i) Bubbles entrained in the liquid in the main pipe or vessel may be carried through into the connecting pipes; (ii) air may leak through faulty joints or through cocks or valves in the connecting pipes; and (iii) air or gas may be liberated from solution in the liquid when its pressure is reduced or its temperature raised. Certain obvious steps may be taken to minimise these risks, but one important measure is to set the gauge so low down, if possible, that a positive pressure exists throughout the whole system. If negative pressures are thus wholly avoided, then the tendency will be for liquid to leak out of the pipe rather than for air to leak in.

Proper measures must also be taken for discharging from the system the air which, in spite of all precautions, manages to find its way in. If the gauge is above the gauge point, the connecting pipes must slope continuously upwards as suggested in Fig. 9 (I), and if at any point an air-lock is unavoidable, i.e. the pipe slopes away in both directions, then there must be a vent cock from which the air can be blown off, and preferably also an air vessel (Fig. 33 (I)) in which air may collect. For differential gauges the vent cocks V and the equalising cocks E on the gauge itself (Figs. 9 and 12) are usually adequate; periodically opening the equalising cock causes a flush of liquid straight through the connecting pipes and may succeed in driving entrapped air back into the main pipe. Afterwards by cautiously opening the vent-cock any remaining air can be expelled from the gauge itself. Note that careless use of the vent-cock may blow the indicating liquid right out of a differential gauge (§ 54). Air bubbles that try to cling to the sides of the connecting pipes during venting can be dislodged

by lightly hammering the pipes if they are of metal, and by vigorously shaking them if they are of india-rubber. A test—though not quite a conclusive one, nor one that is often feasible—to show that the connections of a differential gauge are air-free is to bring the liquid throughout the entire system to rest and to verify that the gauge truly indicates zero head.

If the gauge is specifically installed for measuring *negative* pressures or heads there will be a greatly increased likelihood of trouble due to air leaks. Air vessels such as the one shown in Fig. 33 (I) must now be fitted with a hand pump or the like for exhausting the entrapped air. Sometimes the best plan is to abandon the effort to exclude air from the connecting pipe, and instead to fill it deliberately with air. The system then

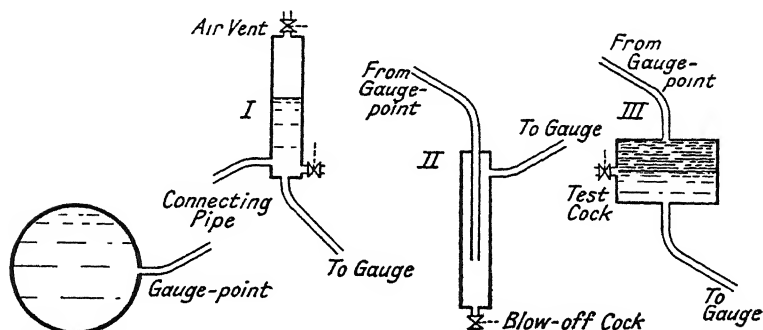


FIG. 33 —(I) Air vessel. (II) Settling chamber. (III) Sealing chamber.

resembles the bubble-type pneumatic gauge (§ 33) except that there is now no air bell. Before taking a reading, a vent cock is opened to admit atmospheric air and to blow all liquid out of the connecting pipe; after the cock is closed the excess air bubbles away into the main pipe and the gauge then indicates the pressure at the gauge point, irrespective of its elevation in relation to the gauge point. As there is now no column of metered liquid in the inlet limb of a glass-tube gauge, Fig. 6 (II), the formula (2) no longer holds good. It must be replaced by the expression $h = h_2 \left(\frac{w_2}{w} \right)$.

46. Connections for Dirty, Viscous, etc., Liquids.

(i) *Grit, rust*, and other solid matter in suspension ought not to be allowed to enter the measuring appliance itself.

Accordingly, if there is danger of this happening, settling chambers should be provided (Fig. 33 (II)) through which the deposits that settle out can periodically be discharged. In very difficult conditions, e.g. the measurement of sewage flow (§§ 124, 193), it may be necessary to make provision for cleaning the pressure tappings in the measuring device—Venturi meter, flume, or the like: this may take the form of a needle which can be pushed through the opening from outside.

(ii) *Viscous or corrosive liquids* may have to be kept out of the connecting pipes altogether by the use of sealing chambers ⁽²⁷⁾ of the sort shown in Fig. 33 (III), set as close as possible to the gauge point. Supposing the metered liquid were a thick oil, this would float above the transmitting liquid, e.g. water, in the connecting pipe; but any movement of the surface of separation may have an effect on the gauge reading serious enough to require correction.

Example: A double-column differential gauge has legs $1\frac{1}{2}$ ins. diameter, and the sealing chambers are 4 ins. diameter. The metered liquid is oil of S G 0.91, the transmission liquid is water, and the indicating liquid is mercury. What head of oil would a gauge deflection of 4.26 ins. represent? Deflection of 4.26 ins. between mercury surfaces will cause a deflection of $4.26 \times \left(\frac{1.5}{4}\right)^2 = 0.599$ in. between surfaces in sealing chambers

From formula (5), § 15, differential head of *water* registered by mercury gauge $= 4.26 \left(\frac{13.59}{1.00} - 1 \right) = 53.5$ ins., which is equivalent to a head of *oil* of $53.5 \times \frac{1.00}{0.91} = 58.9$ ins. Also the head of *oil* to compensate for the difference of level in the sealing chambers $= 0.599 \left(\frac{1.00}{0.91} - 1 \right) = 0.06$ in. Therefore total head difference $= 58.9 + 0.06 = 58.96$ ins. $= 4.91$ ft. of oil.

Note: If the diameter of the sealing chambers is the same as the diameter of the limbs of the gauge, the gauge readings will be wholly unaffected by the presence of the chambers and the transmission liquid.

The arrangement shown in Fig. 33 (III) must be reversed if the transmitting liquid is lighter than the metered liquid.

In any event it has to be remembered that sealing chambers make it more difficult to vent air and vapour from the connecting pipes, for it is now no longer possible to flush out the connections by opening the equalising cock of a differential gauge.

(iii) *Rubber diaphragms*, sufficiently thin and “flabby” as not to influence the pressure to be transmitted, may be used in exceptional conditions; ⁽²⁸⁾ they completely seal off the relatively dirty water on one side from the air-free distilled water on the other, the clean water only being allowed to enter the differential gauge.

47. Damping Methods. If an undamped liquid-column manometer is connected to a point in a pipe through which a liquid is flowing under turbulent conditions, the manometer will rarely give a perfectly steady reading—it will oscillate irregularly through a range of several millimetres, with a periodicity of perhaps $\frac{1}{4}$ or $\frac{1}{2}$ second, and there may be occasional surges of greater amplitude. To make a completely accurate estimate of the mean position of the column is beyond the power of the most experienced observer, and therefore some damping device is often necessary which will bring the indicating column nearly to rest.

Capacity damping automatically occurs when the gauging apparatus embodies containers of relatively large surface area such as gauge wells for staff, hook, or float gauges (Figs. 1, 3, and 4). During any one pressure pulsation there is hardly time for enough liquid to flow through the connecting pipe to or from the well to produce an appreciable effect on the liquid surface which is under observation.

Resistance damping occurs when some obstruction is contrived in the connecting pipe between the gauge point and the gauge. The plug-cock is a convenient form (Fig. 34 (Ia)); it can gradually be closed until the pulsations of the gauge nearly but not quite die out. Unless some slight visible movement of the indicating element remains, the observer cannot be sure that it is still “live.” When rubber connecting pipes are used a screw clamp is very serviceable. The capillary tube (Ib), while free from theoretical objections (§ 48), has the practical disadvantages that its damping effect cannot be regulated, and that as it forms a permanent obstruction it interferes with the flushing of the pipe so desirable for sweeping

air away (§ 45). A plan for overcoming this second difficulty is sketched in Fig. 34 (II); the capillary is set in a shunt circuit in the connecting pipe, in parallel with a full-bore cock which normally is kept shut. The cock is fully opened during flushing, or when the gauge is quickly required to register a change of pressure.

The effective damping of the dial gauges (§ 28) so commonly used in engineering practice is imperative in order to safeguard the rather delicate indicating mechanism of the gauges themselves. It is the water-hammer or inertia pressure from which few pipes are free that constitutes the chief danger: if they act without check and so cause violent kicking of the needle, it is idle to expect the gauge to maintain its calibration

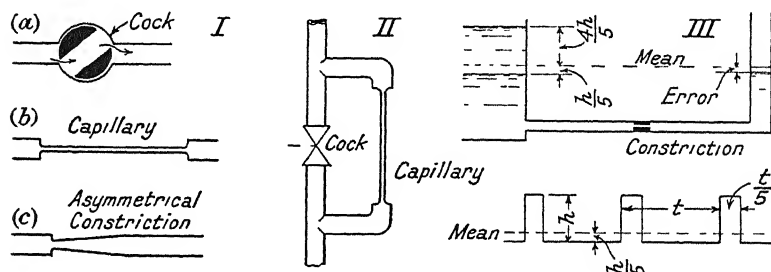


FIG. 34 —Damping methods and damping theory.

for any length of time. Screw-down needle valves are usually recommended for these gauges.

Inertia damping resulting from the inertia of the liquid column in the connecting pipe can rarely be depended on, but the long mercury column in the gauge itself may have a stabilising effect (§ 49 (ii)).

48. Theory of Damping. Two main sources of error may prevent the damped gauge reading from truly representing the arithmetical mean of the fluctuating pressure at the gauge point.

(i) The constriction or obstruction may not be symmetrical, with the result that when the liquid flows momentarily from the gauge point to the gauge the resistance encountered may be different from the resistance when the flow is reversed. If, for example, the asymmetrical constriction shown in Fig. 34 (Ic) were coupled so that the left-hand end led to the gauge

point, the damped reading would be *greater* than the true mean pressure. Although, theoretically, the needle valves used for dial gauges are not free from this objection, the error is usually negligible in comparison with the total pressure.

(ii) A second error may arise if the wave-form of the pressure pulsations is not symmetrical. Suppose that in the tank shown in Fig. 34 (III) the surface level fluctuates through a total range h in the manner represented by the time-head diagram below, the surface being at the upper limit for $\frac{1}{5}$ of the period t and at the lower limit for $\frac{4}{5}$ of the period t . Then evidently the mean level is at a height $\frac{h}{5}$ above the lower limit.

Now let us see what mean level would actually be indicated by the piezometer tube shown on the right if the constriction were in the form of (a) an orifice, (b) a capillary tube. Let h_0 represent the height of the mean level in the piezometer above the lower limit of the tank liquid surface, and let dq represent the very small quantity of liquid that flows into and out of the piezometer at each pulsation. As the flow through an orifice (a) varies as the square root of the head, we may write

$$dq = K\sqrt{h - h_0} \times \frac{t}{5},$$

and
$$dq = K\sqrt{h_0} \times \frac{4t}{5},$$

where K is a constant including orifice diameter, etc. (§ 113).

From these equations we find $h_0 = \frac{h}{17}$, as against the true value $h_0 = \frac{h}{5}$. The damped piezometer is thus in error by

$0.14h$, as suggested in the diagram (Fig. 34 (III)).

But if the capillary tube (b) is dimensioned so that viscous flow occurs, then the flow is directly proportional to the head loss and therefore $(h - h_0) = 4h_0$, or $h_0 = \frac{h}{5}$, which is the correct value. A capillary tube 1 mm. bore and 10 cms. long is likely to give the desired assurance of viscous flow for liquids having viscosities not far from that of water.

A bundle of parallel brass wires packed into the connecting pipe will equally well produce viscous damping.

49. Some other Aspects of Damping. (i) *Detection of pulsations.* The sketch (Fig. 35) shows a simple device that

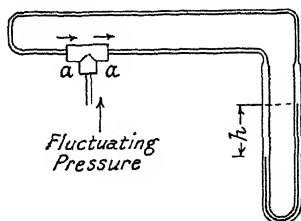


FIG 35.—Detection of pressure fluctuations.

has been suggested⁽²⁹⁾ for observing the maximum range of pressure fluctuations in a pipe. The fluctuating pressure is led to a little valve-box containing two very light non-return valves *a, a*, opening in the direction indicated by the arrows: the valves may be made of tiny discs of celluloid cine-film. The U-tube gauge connected to these

valves will then register a differential head *h* proportional to the difference between the maximum and the minimum pressure in the pipe.

(ii) *Influence on choice of gauge.* At the best, damping can only be regarded as an unwelcome necessity: it may hamper the working of the gauging instruments, and in spite of precautions there may be doubts about the accuracy of the damped readings, especially when small differential heads are being measured. It is therefore worth remembering that some help may be found by correctly choosing the suitable type of gauge. In regard to glass-tube gauges, either of the double-column gauges with an indicating liquid, (II) or (III), Fig. 9, (§ 15) is better than the differential piezometer gauge (I), because in the latter the two liquid columns may pulsate independently, following the unrelated pressure fluctuations at the two respective gauge points; whereas the indicating liquid itself in the gauges (II) and (III) ties the columns together and makes them pulsate *in unison*, whereby there arises a tendency for mutually destructive damping between the two sets of fluctuations. When such gauges, or the single-column gauges (Fig. 6 or Fig. 12), are working under large heads, the inertia of the long mercury column has quite a useful damping effect, promoting steady readings.

(iii) *Leakage.* Although the slightest leakage at any point in the connecting pipe or the gauge itself should be regarded with suspicion, it cannot be allowed *at all* anywhere between

the damping constriction and the gauge. Leakage here, even at the rate of a drop or two per minute, may wholly vitiate the readings of the damped gauge.

50. Care and Maintenance of Gauges. Having now travelled along from the gauge point at which it is desired to learn what the head or pressure is, to the gauge where the actual indications are given or from where they are transmitted, it remains to be said that the variety of instruments available makes it impossible to give instructions for the care of each of them: glass-tube gauges alone, in the following paragraphs, can be given attention in any detail. But certain matters are obvious: recorder charts must regularly be changed, the clock must be wound, and the mechanism cleaned and oiled. Dial gauges must periodically be calibrated against a dead-weight or other standard gauge. Pipe connections must be inspected to ensure that they or their tappings are not choked with dirt. Gauge wells must be cleared of sediment. When there is in addition a long transmission line with electrical equipment at either end, maintenance becomes a more onerous business if only because the transmitter may have to be fixed in an isolated and exposed situation (§ 228).

51. Choice of Indicating Liquid for Glass-tube Gauges. Ideally the indicating liquid should fulfil the following requirements:—

(i) It should not mix with the metered liquid nor stick to the sides of the gauge tube, but should form a sharp, clear meniscus at the surface of separation.

(ii) Its density should be such that the range of heads to be measured can be accommodated on the scale of the gauge.

(iii) Its density should not be subject to temperature changes.

(iv) It should be chemically stable, i.e. not affected by exposure to light or air, or contact with the metered liquid. Nor should it have any effect on the elements of the gauge itself.

Only a few liquids approach this ideal sufficiently to be fit for general use: the best known are:—

Liquid	Approximate Specific Gravity at 60° F	Change in Density per cent , per degree F change in Temperature (for range 50°-70° F)
Mercury . . .	13.59	0.009 per cent.
Acetylene		
Tetrabromide . .	2.98	—
Bromoform . . .	2.9	—
Carbon tetrachloride	1.60	0.07 per cent.
Water	1.00	0.009 „
Paraffin (kerosene) .	0.81	0.04 „
Petrol (gasoline) .	0.74	0.05 „

52. Some Suitable Liquids. In general it is safe to say that mercury should be used whenever possible : its temperature coefficient is so small and so nearly equal to that of water that it rarely need be considered, and, moreover, the water-mercury meniscus is admirably defined. Although there is a temptation to use bromoform or acetylene tetrabromide if the deflection of a mercury gauge is inconveniently small, these liquids are apt to behave unaccountably, and so it may be safer to go one step further and to choose carbon tetrachloride. An excellent substitute for this substance is the liquid sold for use in the “Pyrene” chemical fire-extinguishers ; in concentrated form, as purchased, its specific gravity is about 1.6, and it may be mixed with petrol (gasoline) to give any desired specific gravity from 1.6 down to 0.8.

Although § 15 shows that by choosing the appropriate ratio between the density w of the metered liquid and the density w_i of the indicating liquid, any desired magnification may be obtained, viz. the ratio between the differential head h and the observed gauge deflection h_2 can be completely controlled, yet experimenters rarely find it advantageous to use a greater magnification than about 5. The sensitivity that follows a further increase is apt to be illusory, not only because the temperature coefficient of the indicating liquid may now produce a quite serious error, but because the meniscus in each gauge glass may grow ill-defined and sluggish in movement.

Example : A double-column U-tube gauge uses as its indicating liquid a mixture of petrol and carbon tetrachloride having a specific gravity of about 1.15. The metered liquid is

water, and the gauge is calibrated at a temperature of 55° F. What would be the error in using the gauge at 65° F. ? The change in density of the indicating mixture due to the temperature rise of 10° may fairly be taken as 0.6 per cent. At 55° F. the approximate relation between h and h_2 is

$$h = h_2 \left(\frac{1.15}{1.0} - 1 \right) = 0.150 h_2; \text{ or magnification} = 6.67.$$

At 65° F. the approximate relation is

$$h = h_2 \left(\frac{1.15 \times 99.4}{1.0 \times 99.9} - 1 \right) = 0.144 h_2; \text{ or magnification} = 6.95.$$

The gauge will thus *overestimate* the differential head by about 4 per cent.

If the indicating liquid is a colourless organic compound it may be coloured so that the surfaces of separation are more easily distinguishable: spirit dye or iodine crystals are sometimes useful for this purpose.

If the gauge is of any other form than a plain glass U-tube, the possible effects of the indicating liquid must not be overlooked: mercury, for example, will attack brass containers, unions, etc., and india-rubber will not withstand petrol, paraffin, or carbon tetrachloride. This factor limits the use of the convenient form of differential gauge shown in Fig. 9, whose straight lengths of glass tubing, passing through packed glands, can be replaced more cheaply than a complete bent U-tube can be.

53. Preparation and Calibration of Glass-tube Gauges. Cleanliness is the first essential in securing the regular, symmetrical meniscus that alone makes accurate readings possible; failure here may result in lop-sided surfaces of separation whose position can only be guessed at. According to circumstances, petrol, weak acids, or a very weak solution of potassium permanganate in concentrated sulphuric acid can be used for cleaning the gauge tubes before the indicating liquid is poured into them.⁽³⁰⁾ The indicating liquid is purified thus: rather more than the necessary quantity is thoroughly shaken up with a quantity of the metered liquid, and after settlement the lower layer (or the upper layer, as the case may be) is drawn off and passed through filter paper. If, after the gauge has been in use for some time, there is a tendency for the surface of separation to become cloudy and for deposits

to form on the gauge tube walls, the whole cleaning operation must be repeated.

Except when mercury is used it is rarely permissible to accept the nominal density of the indicating liquid when converting the observed deflection h_2 (Fig. 9) to differential head h . Surface tension effects may operate to disturb the ideal relationship, and consequently a direct calibration is invariably

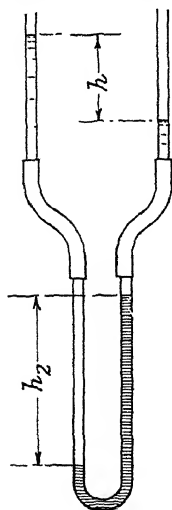


FIG. 36. —Calibration of U-tube gauge.

desirable. It is carried out in the manner shown in Fig. 36. Temporary gauge tubes are arranged above each leg of the U-tube, varying quantities of metered liquid are poured into each, the apparatus is brought to the temperature at which it will afterwards be used, and direct measurements are made of the true differential head h and of the observed deflection h_2 . Alternatively the gauge can be put in parallel with a twin piezometer gauge (Fig. 9 (I)).

While the differential gauge is in normal use there is usually no way of checking the calibration, but at least the zero reading can be checked by shutting one or both of the isolating cocks (Figs. 9 and 12) and opening the equalising cock *E*. When flushing the connecting pipes it is certainly helpful to open and close the equaliser rhythmically so as to work up the indicating column into a violent swinging motion; such brusque treatment, however, is rather unkind on the surfaces of separation, which from their own point of view ought to be carefully protected.

54. Overload Devices. In all types of U-tube gauges a misfortune that may have to be guarded against is the accidental loss of the indicating liquid, such as may occur if the head or the differential head to which the gauge is subjected is momentarily greater than that for which it was designed. Inexpert or careless use of the vent, equalising, or isolating cocks may also bring about the same result, for this may impose on the indicating column the full head in the pipe instead of the differential head only. No matter whether the indicating liquid is blown into the atmosphere or into the

main pipe, it is annoying to have lost it because of the labour involved in cleaning the gauge, calibrating it again, and putting it back into service; besides, the indicating liquid might be a very undesirable impurity in the metered liquid in the pipe-line.

Two common types of protective device are shown in Fig. 37. The U-tube (I) has an expanded part or safety chamber at the top of each limb, of capacity greater than the total volume of indicating liquid; an overload thus has no more serious consequence than to make the metered liquid bubble through the indicating liquid that has been forced

up into one of the chambers. A mechanical device—a float—is sketched in Fig. 37 (II), arranged at the foot of one leg of the U-tube. Normally its buoyancy keeps it hard up against the stop, but should the level of the indicating liquid be forced below the upper part of the float, the float will sink and its conical base will act as a valve, sealing off communication between the two limbs of the gauge.

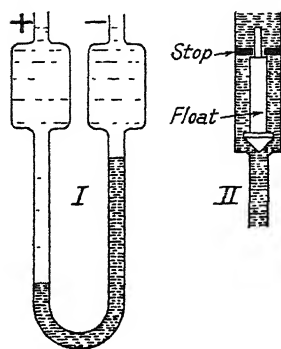


FIG. 37—Overload devices

CHAPTER IV

MEASUREMENT OF WEIGHT AND VOLUME

	§ No.		§ No.
Measurement by weight	55	Calibration of volumetric tanks	58
Volumetric measuring tanks	56	Switching methods	59
Indicating devices for volumetric tanks	57	Flying start-and-stop methods	60
		Standing start-and-stop method	61

A KNOWLEDGE of the weight or volume of liquid contained in tanks and receptacles of various kinds is very often of fundamental importance, not only because of the necessity of such information in industrial plants—e.g. in an oil storage and distribution plant the contents of each tank at any moment must be accurately known—but because in experimental work it is only by collecting liquids in measuring tanks that flow-measuring devices can accurately be calibrated.

The use of “quantity” meters for gauging the contents of tanks is dealt with in Chapter VII.

55. Measurement by Weight. This is the method that is least of all susceptible to error, for weighing machines are very reliable instruments whose indications may be counted on to within perhaps 0.05 per cent. of the maximum reading. The serious objection is the heavy cost—only a very wealthy institution could afford to install special measuring tanks each holding up to 20 tons of water, and machines for weighing them.⁽³¹⁾ When such a degree of refinement is attempted there is one correction to be made that could ordinarily be neglected—it concerns the buoyancy or upthrust of the air on the liquid contained in the tank, which means that the true weight of the liquid, if its density is not very different from that of water, is about 0.11 per cent. greater than the apparent weight registered on the weighing machine.

Small weighing machines arranged for measuring continuously the rate of flow of liquids are shown in Fig. 53, § 80.

56. Volumetric Measuring Tanks. Volumetric gauging of the contents of tanks is made a good deal easier if the vessels are of simple, regular shape, and although this is usually a matter outside the control of those in charge of the gauging—e.g. fuel tanks for marine oil engines may be of quite irregular shape—a designer does sometimes have the chance of arranging a special measuring equipment. If so, a cylindrical steel-plate tank with its axis vertical would naturally be preferred; its deformation under the static pressure of the liquid is negligible, and with modern welded construction its diameter and cross-section can be kept so uniform that volumetric calibration may be unnecessary. Rectangular steel tanks should be well stayed to prevent the sides bulging appreciably when the vessel is full, though admittedly the stays may complicate the calibration.

Masonry or concrete tanks and reservoirs can rarely be considered as absolutely watertight, and thus a leakage correction may be called for. Such a correction is also necessary if other pipes or valves, besides those used for conducting the metered liquid, are connected to the measuring tank, for the experimenter can never be sure that such valves are dead tight. Unless the leakage is excessive it suffices to allow the tank to stand with the liquid surface at its mean level, the inflow being switched off, and to measure the rate at which the surface rises or falls. But it is better to ensure that there is no leakage. This was done at the Hydraulic Machinery Laboratory of the California Institute of Technology ⁽³²⁾ by using concrete tanks lined with $\frac{1}{8}$ -in. steel plate, in which no openings of any kind were permitted: the tanks were drained by vertical-spindle pumps discharging over the side. The group of three tanks was arranged as shown in Fig. 39 (II), § 59.

57. Indicating Devices for Volumetric Tanks. In use, the quantity of liquid in the receptacle is estimated solely from observation of the surface level, for which purpose a wide range of devices is available. Unless there are sound reasons against it, the plain piezometer tube (§ 12) is a safe choice. Float gauges are convenient also, while the electrical indicating plumb-bob (§ 34) was preferred for the high-precision measuring tanks shown in Fig. 39 (II). Pneumatic gauges (§§ 31, 33) have the advantage that the indicating instruments

can be grouped under the eye of the supervising official, the bubble type with hand-pump having a high degree of accuracy also in its favour. Dipsticks and dip-tapes (§ 6) are simple and satisfactory.

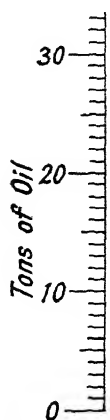


FIG. 38. —
Calibrated
scale for
oil storage-
tank.

The method of graduating the scales of the indicating instruments—whether in units of volume or units of weight—must be carefully considered. If the device unmistakably indicates liquid level—e.g. a float gauge, dipstick, or staff gauge in any of its forms—then it could be made to indicate directly the volume in the tank. But pneumatic gauges really measure *pressure*, and to some extent their readings are meaningless unless the density of the measured liquid is known. In a storage tank as usually built, however, of fairly uniform circular cross-section, in which the density of the liquid does not undergo wide variations, the pneumatic gauge can be correctly graduated in units of *weight*.

Example: The quantity of oil in a cylindrical storage tank is to be indicated on a single-column mercury manometer working in conjunction with a pump-operated bubble-type pneumatic installation. The tank is 25.3 ft. mean internal diameter, the S.G. of the oil is 0.92, the area of the mercury container is 10.6 sq. ins., and the sight-glass is $\frac{1}{2}$ in. diameter. How should the manometer scale be graduated to show the weight of oil in the tank in tons?

The ratio $\frac{a}{A}$ is $\frac{0.7854}{4 \times 10.6} = 0.0185$. Inserting this value in formula (7), § 33, we find $h = h_2(1 + 0.0185)\frac{13.59}{0.92} = 15.02h_2$. Now area of tank = 503 sq. ft., consequently weight of oil in 1 ft. depth = $\frac{503 \times 62.4 \times 0.92}{2240} = 12.87$ tons. Also manometer deflection corresponding to 1 ft. depth = $\frac{1}{15.02} = 0.0665$ ft., therefore 1 ton is represented by

$$\frac{0.0665}{12.87} = 0.00517 \text{ ft.} = 0.062 \text{ in.}$$

on the manometer scale, which can then be calibrated as in Fig. 38.

It should be noted that although the numerical value of the specific gravity is introduced to make the calculation clear, it actually does not affect the final result at all, and thus temperature changes have *no influence* on the accuracy of the scale.

58. Calibration of Volumetric Measuring Tanks.

The object of this operation is to determine very carefully the area of the liquid surface at various levels, so that the desired relationship between depth and volume may be established. When cylindrical steel tanks are used for commercial purposes it usually suffices to measure with a steel tape the outer circumference of each ring of plates; then from a knowledge of the plate thickness the area required is easily calculated. This method gives sufficiently accurate results even if the nominally circular section is markedly out of truth. Suppose the (originally) circular section to be distorted into an ellipse having the same circumference but having a minor axis 5 per cent. shorter than the original diameter of the circle: then the reduction in cross-sectional area will only be 0.16 per cent. It is to be noted also that the variation in area resulting from thermal expansion of the plates is usually negligible compared with the volumetric changes of the liquid itself as the temperature changes.

The circumferential lap-joints of riveted tanks may complicate the calibration, and for special tanks intended to serve as primary standards of flow measurement it is preferable, as already suggested, to have butt-welded seams. Rectangular tanks may be dealt with by lowering a set of plumb-lines near each wall, measuring the distance between the lines, and then taking off-sets from the plumb-lines to the walls. The estimation of the small areas to be deducted, represented by angles, stays, and stiffeners, may be tedious.

Whenever calibration by linear measurement is not practicable, and preferably also—as a check—even when it is, calibration must be done by a standard measuring vessel, whose contents are discharged time after time into the main tank, the corresponding liquid levels being successively recorded. From this record a calibration curve or a calibration chart can be prepared, permitting the capacity of the measuring tank to be read off, or enabling the depth-measuring device to be graduated. For small tanks, standard certified measures of capacity—e.g.

4-gallon measures—may be available; for larger ones a special measuring vessel may have to be made, and its capacity found by accurate weighing. Points to be noted in this connection are: during the calibration the temperature must be kept steady and should be recorded; a uniform interval must be allowed for the standard measuring vessel to drain into the main tank; the depth-measuring device used during calibration should be the one that it is subsequently intended to use for normal measurements.

59. Switching Methods. Although this question—the question of turning the incoming liquid into the measuring tank

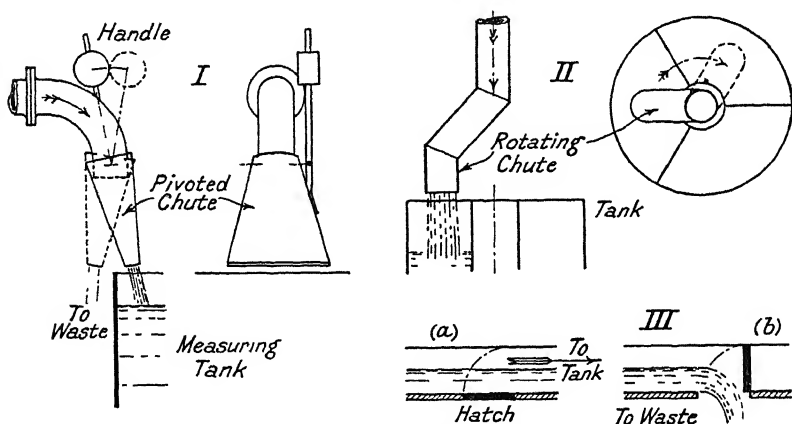


FIG. 39.—Switching methods.

and then switching the flow away again—might equally well be considered in connection with absolute methods of flow measurement (§ 79), it is more convenient to regard the switching apparatus as part of the measuring tank. The simple lay-out sketched in Fig. 39 (I) is adapted for small flows; the pivoted chute is shaped so that the liquid issues from it in the form of a thin sheet, and thus the moment at which the flow begins to enter the tank, as the handle is smartly jerked over, is clearly defined. A revolving chute⁽³²⁾ is shown in Fig. 39 (II); during the switching movement it is driven at a uniform speed by an electric motor, and the exact moment at which the centre of the stream passes across the radial partitions between the collecting tanks is recorded with the help of

an electric contact and electric chronograph (Fig. 49). A pivoted wooden hatch (Fig. 39 (III)) was used during experiments on the discharge over a dam,⁽³³⁾ in which the water entered the measuring tank along a wooden flume.

An interesting scheme was devised at the Walchensee Research Institute for switching into a measuring tank of 1600 cubic metres capacity a flow that might attain a maximum of 4 cu. m./sec. (140 cu. ft./sec.). It is illustrated in Fig. 40. From an experimental channel 2.5 metres wide the water passed first into a forebay, and then either to waste or into the tank; identical motor-driven taintor gates controlled the direction of the water, the gates being interconnected as shown so that when one was fully closed the other was fully open. To allow for the appreciable time occupied by the opening and closing movement—about 3 seconds—a special system was followed. At the beginning of a test the moment at which the gate leading into the measuring tank *began to open* was noted, and at the end of the test, the moment at which this gate *began to close*. It was

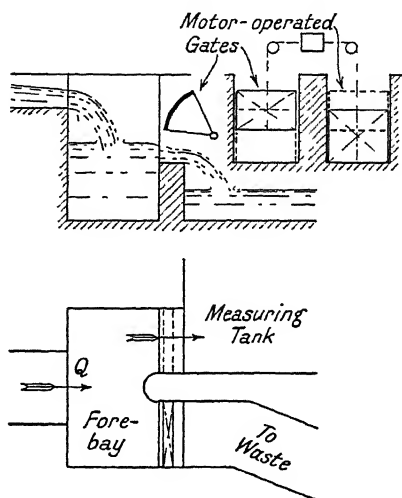


FIG. 40.—Switching system for 1600 cubic metre tank.

proved⁽³⁴⁾ that the intervening period truly represented the equivalent time that would have been needed for filling the tank if opening and closing of the gates had been instantaneous.

60. Flying Start-and-stop Methods. These are indicated if it is impracticable to provide switching gear and the flow to be gauged is therefore continually discharging directly into the measuring tank. The essential requirement is a drain valve so big that when it is open the liquid drains through it quickly enough to ensure a reasonably low surface level in the tank. With a uniform discharge this level would soon be stabilised.

(i) Assuming a *weighing* tank to be used, the weighing machine would be set for a load about 5 or 10 per cent. greater than that corresponding to the stabilised conditions now existing. Then the drain valve would quickly be closed, and the operator would closely watch the weigh-beam: as soon as it rose off its lower stop, he would note the time. Quickly adjusting the load now to suit a nearly full tank, he would again note the time when the beam rose. Finally the waste valve would be fully opened before the tank began to overflow.

Although it is true that the dynamic thrust or impact-pressure of the liquid falling into the tank will create an error in the observed weight, its amount can fairly be assumed not to change appreciably as the tank fills, and it will therefore have no effect on the net weight of liquid collected, obtained by subtracting the initial from the final scale reading.

(ii) The equivalent operations in a *volumetric* tank are to note the times at which the float gauge or the piezometer column reaches a lower and an upper level; but now there is another possibility of error to be watched. Especially if the float gauge is housed in a separate gauge well, it will always lag slightly behind the rising liquid surface in the main tank, and therefore a sufficient interval must be left, after the shutting of the drain valve, for the lag to build up. As regards accuracy, the personal equation of the experimenter may be a more important factor in correctly observing the moment at which a moving scale or a rising liquid column passes a given graduation, than it is in noting the time at which a switching movement is made; but in any event a flying-start gauging would hardly be attempted if a switching system could be devised. A final point is that whereas in switching methods the liquid surface is always allowed to become calm before readings are taken, this advantage is denied the flying-start method.

61. Standing Start-and-stop Method. A special technique has sometimes to be devised when the liquid can neither be switched away from the measuring tank nor allowed to flow continuously into it. The difficulty here is to make a suitable correction for the liquid that enters the tank during the period of opening and closing the valve or sluice whose discharge is being measured. During the calibration of the

Assuan Dam sluices,⁽³⁵⁾ which involved the collection of discharges up to 90 tons per second in a masonry tank holding 22,000 tons of water, the following method was developed: First the initial depth in the nearly empty collecting tank was measured. Then the selected sluice was opened as rapidly as possible, held open for the desired period, and closed again, the time for each of the three phases—opening, open, and closing—being accurately noted. The whole of the water flowing through the sluice had meantime fallen into the tank, where it was in such a violent state of commotion that the final reading of the tank water level could not be taken for two hours.

To the total volume of water collected a correction then had to be made for leakage, and another one to compensate for the discharge during the opening and closing phases. This second correction was arrived at by repeating the test under identical conditions, but this time the gate was continuously opened and closed a number of times, so enabling the average rate of discharge during one opening and one closing to be computed. Various check experiments verified the figure finally obtained for the discharge through the fully-open sluice.

CHAPTER V

MEASUREMENT OF VELOCITY

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62. Scope and Purpose of Velocity Measurements.

To define completely the velocity at a point in a liquid we require to know: (i) the magnitude of the velocity, (ii) the direction of the velocity with respect to some basic system of co-ordinates, and (iii) the "sense" of the velocity, i.e. whether the motion is towards or away from a given station. In experimental and research work information must be sought on all of these matters, but more often the direction and sense are known (or assumed to be known), and only the magnitude of the velocity must be measured. If this magnitude is constantly fluctuating, as it nearly always is in practice, then the measurement must nevertheless give the correct mean value of the velocity.

The various routine methods of measuring rate of flow which depend upon velocity determinations are discussed in the appropriate chapters (in pipes, Chaps. VIII and IX; in open streams, Chap. X); in this chapter the velocity-measuring instruments themselves are described and their characteristics explained.

63. Floats and Visible Velocity Indicators. The most primitive way of estimating the surface speed of a flowing stream is to drop on to its surface a twig or other object that will float, and to time the object over a known distance. In favourable conditions stream gaugings accurate enough for engineering purposes may be made in this manner (§§ 153-155).

In the Hydraulic Research Laboratory at Leningrad ⁽³⁶⁾ the flow in models of rivers and estuaries has been studied by releasing at the upstream end of the model a succession of small luminous floats, the whole apparatus being then photographed at regular intervals, time exposures of known duration being made on a single plate. On development, the track of each float was represented by a series of dashes, and by comparing the lengths of the dashes with linear scales included in the photograph, the magnitude of the velocity at various points could be computed.

When the direction only of the velocity is wanted, and the motion takes place in conditions allowing it to be observed or photographed (e.g. in a channel with glass observation windows), then fine powder such as oatmeal or oak sawdust flour can be put in the water to make the flow visible. Even the micro-organisms in domestic tap-water will serve if they are powerfully illuminated and viewed through a high-power microscope.⁽³⁷⁾ Also serving as minute floats are jets of dye or other colouring matter injected at suitable points in the system.

Still another method is to tie threads of wool or cotton to a light wire frame immersed in the experimental apparatus; they act as streamers which show the direction of the currents quite well.

INSTRUMENTS DEPENDING ON IMPACT PRESSURE

64. The Pitot Tube. Within its range this instrument offers the most accurate and often the most convenient way of measuring the magnitude of velocities, not least among its advantages being that its effective cross-section may be made so small— $\frac{1}{100}$ ft. diameter or less—that, compared with the total cross-section of the flowing stream it can almost be regarded as a geometrical point. For the same reason it creates relatively little disturbance in the stream.

In the elementary form represented diagrammatically in Fig. 41 (Ia) a glass tube is shown with a nozzle pointing upstream, a current moving with velocity v impinging axially on the mouth of the tube. The resulting dynamic pressure or impact pressure causes the liquid to rise inside the tube by an amount h above the liquid surface level; it is by measuring

this height h that the velocity v may be determined. The relationship between the two quantities is

$$v = C\sqrt{2gh} \quad . \quad . \quad . \quad (8)$$

where C is an empirical coefficient depending on the shape of the nozzle and on other variables.

The same simple instrument may be used as in Fig. 41 (Ib) for measuring the velocity of the jet of liquid issuing from a tank, while (II) shows how the velocity in a closed pipe can be found. Here it is to be noted that since the effective head h is that due to the impact pressure only, we must now measure a *differential* head, viz. the difference between that existing at the mouth of the nozzle, and that measured at the side of the pipe. The

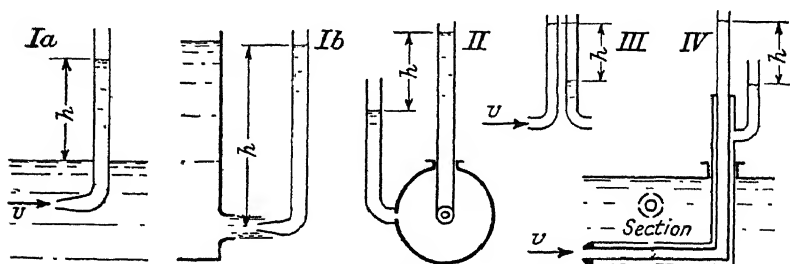


FIG. 41 — Principle of Pitot tube.

nozzle itself is sometimes referred to as the *impact* orifice, and the tapping in the pipe wall is called the *static* orifice.

For a given velocity the differential head generated can be increased by using, instead of a true static orifice, a trailing orifice pointing downstream as at (III), in which a suction effect is created. Another form having important practical applications is shown at (IV); here the static orifice consists of a ring of small holes drilled in a circumferential sleeve surrounding the impact orifice.

In general, then, there are two components to a Pitot-tube gauging outfit: (i) the *primary* device consisting of impact and static openings in which the differential head is generated, and (ii) the *secondary* device in which the differential head is measured, and which may take one of the numerous forms described in Chapter I. Although in the simplified diagram, Fig. 41, the two components are combined, in practice they

may naturally be separated and linked only by flexible connections, each component being located where most convenient.

65. Pitot-tube Coefficients and their Determination. Before the Pitot tube can be used the value of the coefficient C in the equation $v = C\sqrt{2gh}$ should accurately be known. To do this the instrument must be *rated* or calibrated—it must be towed at various known speeds through still water in a rating channel (§§ 73, 74) and the corresponding differential heads noted. It is sometimes possible to carry out the rating in the throat of a Venturi meter,⁽³⁸⁾ where the velocity distribution is unusually uniform; and other comparative methods are also available.

By these means it has been established that under suitable conditions the coefficient has an almost invariable value of 1.00, irrespective of the velocity and of the shape of the impact orifice, so long as the Reynolds number based on the outer diameter does not fall below 100⁽³⁹⁾—which would only happen with extremely viscous liquids. But the value $C = 1.00$ has only a limited significance; it applies only to liquids flowing steadily in parallel filaments, and it has to be modified as indicated in § 67 for ordinary conditions of pulsating, turbulent flow. Nor does it apply to the type of tube with a downstream orifice (Fig. 41 (III)) which has a variable coefficient C of 0.87 or less (§ 131) depending on the magnitude of the velocity.

Values of C as low as 0.57 can be realised by using a specially shaped static opening in which a Venturi suction effect is created.⁽⁴⁰⁾

66. Effect of Oblique Flow. There are two ways of regarding the effects of obliquity of flow—which occurs when the axis of the impact orifice no longer is set parallel with the direction of flow, but makes an angle α with this direction. We may first think of the orifice as being turned in succession to various angles with the direction of the constant velocity v (Fig. 42 (I)). By so doing it is found that so long as α does not exceed about 10° , then the differential head generated is hardly affected, or, in other words, the Pitot tube continues to give a correct indication of the magnitude of the velocity. This is very convenient, for it means that when measuring velocities whose direction is known there is no need to be over-scrupulous

in setting the axis of the tube precisely in the specified direction.

But the actual conditions of discharge measurement rarely enable us to profit by this helpful characteristic. These conditions, representing the second aspect of oblique flow, are to be seen in Fig. 42 (II); the axis of the Pitot tube is fixed,

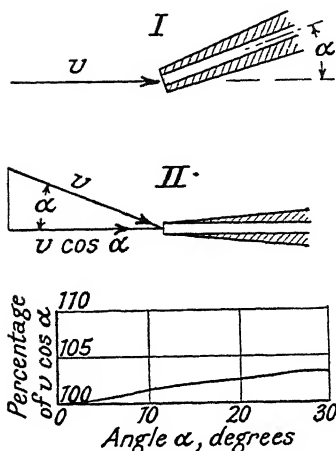


FIG. 42.—Oblique flow on Pitot tube.

what is now to be measured is the value of the velocity component $v \cos \alpha$ as the liquid filaments moving with uniform speed v make various angles α with the axis of reference. This component is frequently termed the *cosine component*. From what was said about Fig. 42 (I) it is clear that the Pitot tube cannot measure the value of $v \cos \alpha$ accurately, because as the angle changes and $v \cos \alpha$ changes, the observed differential head h remains *virtually unaltered* until α exceeds 10° or so. It follows that the observed

value of $\sqrt{2gh}$ is always *greater* than the true value of $v \cos \alpha$, the disparity, depending to some extent on the shape of the impact orifice, being least with hemispherical noses of the type IV, Fig. 41. For impact orifices of the type shown in Fig. 42, the graph gives the relationship⁽⁴¹⁾ between the angle α in diagram II, and the value of $\sqrt{2gh}$ expressed as a percentage of the cosine component $v \cos \alpha$.

Example: When a stream of water impinges at an angle of 20° on to a Pitot tube, the differential head generated is found to be 1.22 ft. What would be the cosine component and the velocity of the stream?

From Fig. 42 we see that the percentage of $v \cos \alpha$ corresponding to an angle of 20° is 102.3, therefore

$$\frac{\sqrt{2gh}}{v \cos \alpha} \times 100 = 102.3.$$

Inserting appropriate values, thus,

$$\frac{\sqrt{64.4 \times 1.22}}{v \cos \alpha} \times 100 = 102.3,$$

we find that $v \cos \alpha = \text{cosine component} = 8.65 \text{ ft./sec.}$, and

$$v = \text{velocity} = \frac{8.65}{\cos 20} = 9.20 \text{ ft./sec.}$$

67. Effect of Turbulent Flow. The usual conditions for a Pitot tube installed for flow measurement in a pipe are represented symbolically in Fig. 43. The impact orifice is set with its axis parallel with the *average* direction of flow, and as a consequence of the turbulent motion of the liquid, currents of varying kinds impinge on the orifice; axial currents may vary in magnitude, as exemplified by v_a and v_b , and currents of the same magnitude may vary in direction, e.g. v_c and v_d . But the experimenter has no other knowledge of these complex and rapidly varying phenomena than what is conveyed to him by the differential gauge coupled to the Pitot tube; from its indications *only* he has to arrive at a

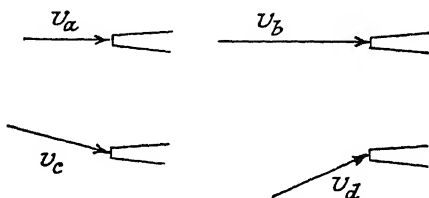


FIG. 43—Velocity variations in turbulent flow.

reasonably accurate estimate of the mean value of the cosine components of these successive velocities—the value, that is, of their axial components which are alone of any use in computing rates of discharge.

One difficulty is already clear enough—from the observed value of the differential head h there is no way of calculating the true value of $v \cos \alpha$ unless the angle α is known and a curve such as the one in Fig. 42 is available. There is also another difficulty. Supposing that the numerical values of the successive axial velocities v_a and v_b in Fig. 43 are respectively 8 and 10 ft./sec., then the mean of these is 9.00 ft./sec. But the mean of the respective differential heads $\frac{8^2}{2g}$ and $\frac{10^2}{2g}$ is $\frac{82}{2g}$, and thus the mean velocity as computed from the mean of the observed differential heads—which is what a properly damped gauge should show (§ 48 (ii))—is $\sqrt{82} = 9.05 \text{ ft./sec.}$ Even

fluctuations of axial velocities, then, tend to make the differential gauge over-estimate the mean velocity. The only practical way of taking into account these two possibilities of error is to give to the experimental coefficient C a value which will, on the average, compensate for both. This value may vary between 0.99 and 0.97, diminishing as the degree of turbulence increases: if no other guidance is available, the value 0.976 has been recommended,⁽⁴¹⁾ that is, the mean cosine component or the *mean axial velocity* $= 0.976\sqrt{2gh}$.

68. The Pitot Cylinder. This title is here used to describe a modification of the Pitot tube which gives the instrument the power of discriminating between currents approaching it from different directions; if the plane containing

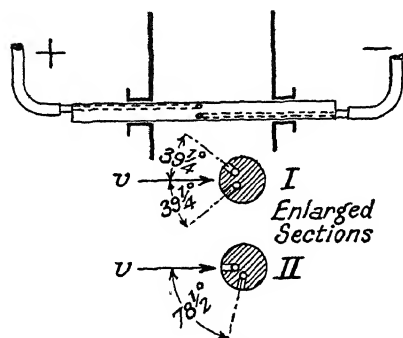


FIG. 44.—The Pitot cylinder.

the velocity vector is known, then the angle of the vector within that plane can fairly accurately be measured.⁽⁴²⁾ In Fig. 44 the Pitot cylinder or rod is seen placed transversely across a parallel passage in which it is assumed that the liquid is moving parallel with the walls. There are two pressure orifices in the walls of the cylinder; they

are carefully drilled so that the angle included between them is $78\frac{1}{2}^\circ$ and they communicate with a differential gauge. An external pointer shows the angular position of the zero line midway between the openings, and a suitable scale shows the longitudinal position of the openings relative to the walls of the passage.

In use the cylinder is pushed along axially until the orifices lie in the plane it is desired to explore, and then the cylinder is slowly turned until the differential head registered is nil. The direction of the zero line then exactly coincides with the direction of the velocity v (Fig. 44 (I)), and it can be read off by means of the external pointer. The pointer is now turned through exactly $39\frac{1}{4}^\circ$, so ensuring that one orifice directly faces the current, thus acting as an impact orifice, while the

other serves as a static orifice. (The angle $78\frac{1}{2}^\circ$ is specially chosen to give this result.) As the apparatus now acts as a Pitot tube, the observed differential head will enable the magnitude of the velocity v to be computed (Fig. 44 (II)).

69. The Pitot Sphere. While the Pitot cylinder is responsive to velocities in two dimensions, the Pitot sphere is intended to measure the magnitude and direction of currents on a universal or three-dimensional basis. It has five pressure orifices pierced in the surface of a sphere formed on the end

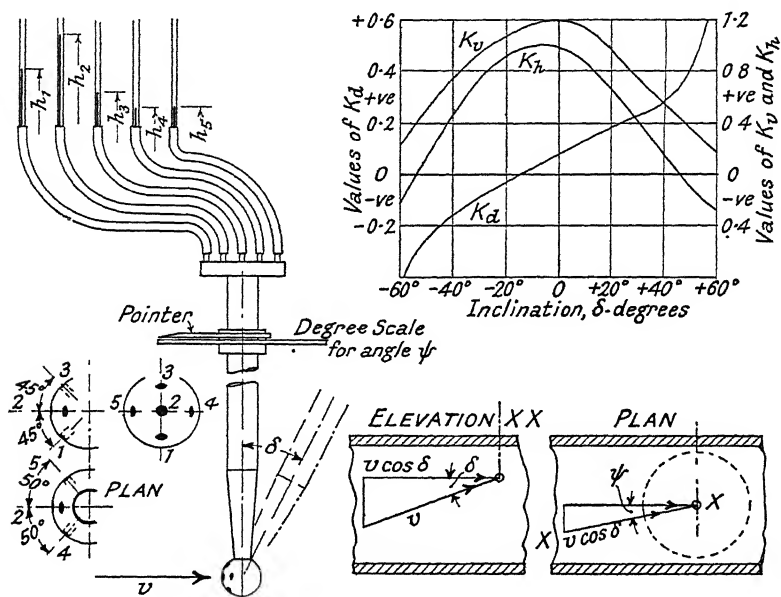


FIG. 45.—The Pitot sphere.

of a stem (Fig. 45), each orifice being connected to its own piezometer tube. The stem can be turned about its axis through angles ψ that can be read by an external pointer moving over a fixed degree scale. During calibration the stem also may be swung out of the vertical, tilting about the horizontal diameter of the sphere, through angles δ .

To calibrate the instrument it is mounted with the stem set at the desired inclination δ , as shown by broken lines in the diagram, in a stream of known horizontal velocity v , at a point

at which the static pressure head h is also known. The stem is then slowly rotated about its axis until the readings h_4 , h_5 of the manometers connected to orifices 4 and 5 are exactly equal, and the pointer or external scale adjusted and clamped so that the reading of the angle ψ is zero. The values of v , h , h_1 , h_2 , h_3 , and h_4 are now read off. By taking similar sets of readings with other values of the angle δ , calibration curves (Fig. 45) may be plotted between the angle δ and the three coefficients k_a , k_v , and k_h , these coefficients having the following values:—

$$k_a = \text{direction coefficient} = \frac{h_3 - h_1}{h_2 - h_4},$$

$$k_v = \text{velocity coefficient} = \frac{h_2 - h_4}{v^2/2g},$$

$$k_h = \text{pressure head coefficient} = \frac{h_2 - h}{v^2/2g}.$$

Within certain limits experiment shows that for a given Pitot sphere these coefficients are independent ⁽⁴³⁾ of the magnitude of the velocity v . (Note that in the specimen calibration curve, here reproduced, the angle δ is regarded as having a *negative* value when the stem is in the position shown by broken lines.)

To use the Pitot sphere to determine, at a given point in (say) a pipe, the magnitude and direction of the mean velocity as well as the pressure head, the stem is set normally to the pipe axis, the centre of the sphere is brought to the specified point, and the zero of the ψ -degree scale is fixed parallel with the pipe. The stem is now rotated until piezometers 4 and 5 give identical readings, all the piezometers are read, and the angle ψ on the degree scale is noted. From the values of h_1 , h_2 , etc., the direction coefficient k_a is calculated, and from the corresponding value of k_a on the calibration curve the angle δ is read off; and as ψ and δ are thus both known, the *direction* of the velocity is completely defined. Using the same value of inclination δ , the values of k_v and k_h are also taken from the calibration curve, and these, in conjunction with the expressions which define them, permit the *magnitude* of the mean velocity v and the *pressure head* h to be computed. From the elevation and plan of the pipe included in Fig. 45, it is clear that the mean velocity component parallel with the pipe axis has

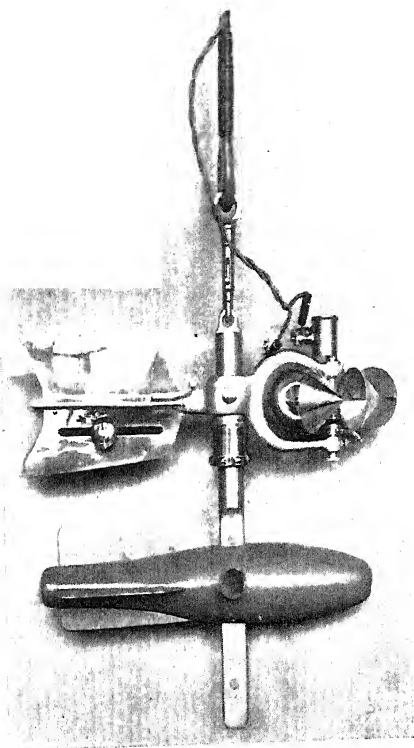


FIG. 46.—Cup-type current meter.
(E. R. Watts & Co. Ltd.)
[To face page 80.]

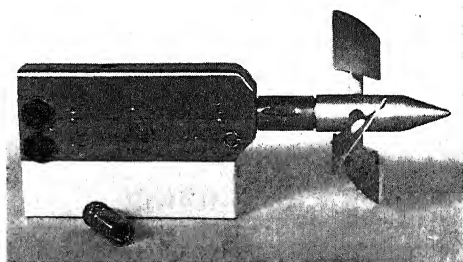
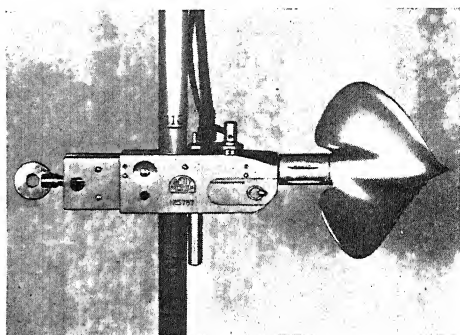


FIG. 47.—Propeller-type current meters. (Dr. A. Ott.)
(*Above*: screw meter; *below*: spoked meter.)

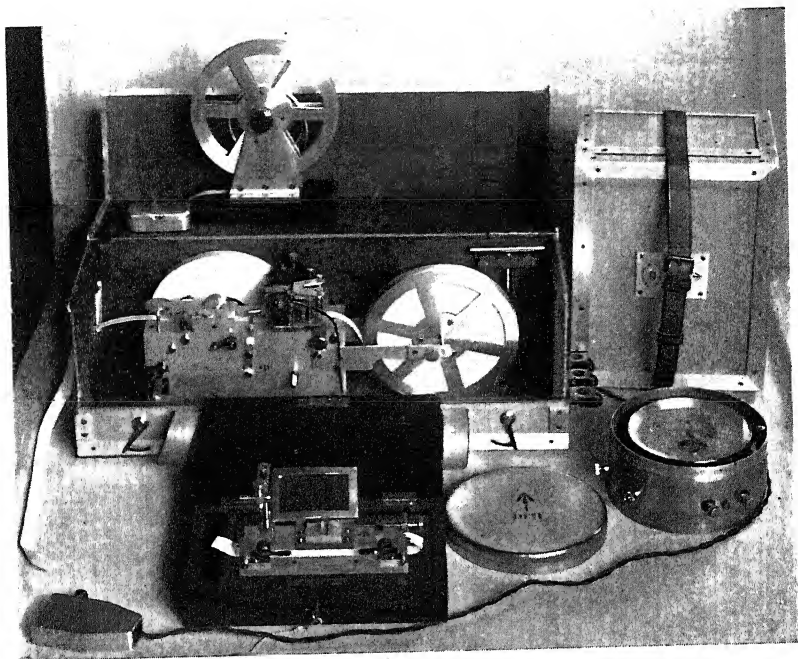


FIG. 49.—Tape chronograph outfit.



FIG. 50.—Current meter rating station.

[To face page 81.]

the value $v \cos \delta \cos \psi$. Naturally the velocity directions here shown would not be expected in a long straight pipe.

As both the Pitot cylinder and the Pitot sphere are as yet relatively untried appliances, engineers may be justified in accepting with a certain reserve the information they yield.

CURRENT METERS

70. Types of Meter. All current meters consist of a system of rotating blades or cups mounted in a frame in such a manner that when placed in the flowing water at the point at which the velocity is to be measured, the rotating element will turn at a speed definitely related to the water velocity. The observed speed of rotation thus gives a measure of the velocity.

The two main classes of instrument are—

- (i) The *cup* or *Price* meter, which revolves about a *vertical* axis, that is, an axis perpendicular to the direction of flow of the water.
- (ii) The *screw* or *propeller* meter, which revolves about a *horizontal* axis, that is, an axis parallel to the direction of flow.

The use of the Price meter is confined almost exclusively to English-speaking countries ; in America it is often known as the Gurley meter. On the Continent of Europe names of makers of propeller meters are Ott, Amsler, and Stoppani ; in America these meters are associated with the names Haskell, Hoff, and Fteley-Stearns.

71. Construction of Current Meters. (i) A typical *Price* meter, as made by Messrs. E. R. Watts & Co., Ltd., is illustrated in Fig. 46. Six conical cups or buckets form the wheel, whose short, vertical spindle revolves in bearings in a stiff frame or yoke ; the pivot which supports the weight of the wheel is of hardened steel, and the bearings are of sapphire. Above the upper bearing is the contact box containing the electrical contacts by which signals are transmitted to the observer ; at every revolution of the wheel, or at every 5 revolutions, the contacts are closed by a simple cam or eccentric device. The meter illustrated is *cable-suspended*—it is freely hung in the water from a steel cable which is kept taut by a stream-lined lead weight or sinker, and fins on the tail

of the yoke maintain the frame truly in the direction of the current. To prevent damage to the bearings during transport, a locking device is provided which clamps the wheel and relieves the pivot of its weight.

(ii) There are two types of *propeller* meter, and they are represented in Fig. 47; both of these are manufactured by the firm A. Ott. The upper engraving shows a true *screw* meter, in which the revolving element is of integral helicoidal form. The type shown below, having separate blades each fixed to the end of a spoke, is referred to as the *spoked* meter. For a given current velocity the spindle speed of the propeller meter is much higher than it is in the cup meter, and it therefore usually embodies a worm and worm-wheel so that contact is made every 25, 50 or 100 revolutions of the spindle. It is an advantage if the spindle has ball-bearings enclosed in an oil-bath.

The instruments shown in Fig. 47 are *rod-mounted*, being clamped to a rigid support. Meters so held have characteristics different from cable-supported meters.

72. Signalling Devices for Current Meters. Audible electric signals are found satisfactory for routine velocity determinations, as in river and stream gauging. Light, twin flexible cable connects the meter, which may be many feet below water level, to the buzzer, bell, or telephone at the observing station (Fig. 48). A voltage not greater than 4 is sufficient, and it may be provided by dry cells or a secondary battery. When the meter is in position the observer counts the signals and notes the time with a stop-watch.

A permanent record of the signals is sometimes desirable, and it is essential if a number of current meters are working simultaneously (§§ 140, 142). Such a re-

recording outfit comprises a tape chronograph, and a chronometer or an electrically controlled pendulum which will emit signals at accurately adjusted intervals—say every second or every 5 seconds. Each of the current meters and also the chronometer are connected to its own electro-magnet on the

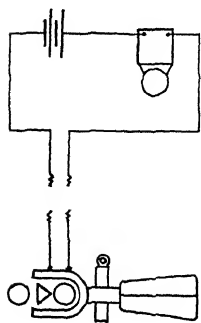


FIG. 48. — Electric signalling circuit for current meter.

chronograph ; as each signal is received there the electro-magnet deflects a pen or draws down a pricker which leaves a trace on the paper strip which is fed forwards by clockwork. By comparing the trace of the current meters with the trace left by the chronometer, the periodicity of the current meter signals can be found. The illustration (Fig. 49) clearly shows a typical chronograph with its clockwork, electro-magnets, and spools ; to the right is the chronometer, and in front is an appliance for measuring the pitch of the signals recorded on the tape.

Special signalling methods are called for if the current meter is to indicate the direction and sense of the velocity in addition to its magnitude. It is possible to do both of these by using a system of multiple contacts, of which one set is controlled by the angular position of the pivoted tail of the meter ; then by comparing the shapes of the chronograph records, the computer can tell whether the meter was revolving clockwise or counter-clockwise, and what was the inclination of the axis. Meters can also be made with a magnetic compass enclosed in a watertight casing, a separate electric transmission system signalling the position of the needle relative to the casing.

73. Rating of Current Meters. *Rating* is the name given to the fundamentally important operation of finding the relationship between the observed number of electric signals transmitted from the current meter in unit time, and the velocity of the water flowing past the meter. The elements of a rating station ⁽⁴⁴⁾ are shown in Fig. 50. Above a long, straight channel filled with water at rest a pair of carefully-levelled rails are laid ; they form a track for an electrically-driven car which picks up its current from a conductor rail, and in addition there are ground contacts spaced at fixed distances apart. A large revolving drum mounted in the car carries a chart on which are recorded the successive impulses received from the ground contacts, and also the signals transmitted from the current meter under test which is hung from the car. In use the car is driven along the track, and thus tows the current meter through the water at various selected speeds ; and from the known speed of the chart and from the signals recorded on it the desired rating curve can be drawn.

At other kinds of rating stations the rating car is pulled

along by a stationary motor-driven winch at the end of the tank, where the control and recording instruments are grouped.⁽⁴⁵⁾ It is even possible to collect useful information by pushing the car along by hand.

Precautions necessary to ensure reliable rating include—⁽⁴⁶⁾

- (i) The water in the tank must be allowed to come completely to rest after each run, before beginning the next.
- (ii) The meter must not be allowed to approach too closely the sides or bottom of the rating channel.
- (iii) The channel should preferably not be less than 4 ft. wide and 5 ft. deep, and it should be long enough to permit a clear run at constant speed of at least 50 ft. A total length of 300 ft. is thus advisable.
- (iv) The meter should be supported by the kind of rod or cable it is intended to use during the velocity observations in the field.
- (v) The speed at which the meter is towed should not approach too closely the speed at which surface waves move along the channel.

At *circular* rating stations the meter is towed in a circular path in a shallow pond or reservoir by hanging it from the end of a boom which revolves about a vertical axis. Unless the boom is very long—80 ft. or so—the curved path of the meter brings an element of doubt into the procedure, and, moreover, the large water area may be disturbed by wind.

Another way of utilising a reservoir is to mount the meter in front of a power-driven launch which is steered past landmarks ashore whose measured distance apart permits the velocity to be accurately computed.

A method of rating a current meter in moving water, by holding it in the jet issuing from a sluice whose discharge is known, is mentioned in § 207.

74. Rating Curves and their Validity. From the results of the rating tests, rating curves giving the relationship between meter speed and water velocity may be plotted in either of the two ways shown in Fig. 51. Although the upper curve gives directly the connection between revolutions per second of the meter and water velocity in feet per second, the lower curve enables the information to be scaled off more

accurately, especially at low velocities. Both of them refer to a cup meter. Instead of plotting a rating curve, a rating table is sometimes prepared; a part of such a table is here reproduced:—

Revolutions per Minute.	Velocity in Feet per Second									
	0	1	2	3	4	5	6	7	8	9
30	1 088	1 124	1-160	1-196	1 232	1 269	1-305	1 340	1-376	1-412
40	1 449	1 486	1-522	1-558	1-594	1 630	1-666	1-703	1-740	1-776
50	1-812	1 848	1-884	1-920	1-956	1 992	2 028	2 065	2 101	2 037
60	2 172	2-208	2-244	2-280	2 316	2-353	2-390	2 427	2 463	2 500

The rating of a meter will not hold indefinitely; after the meter has been used for a specified time—say 100 hours—or after it has been accidentally damaged or after any adjustment, it ought to be sent to the station for re-rating.

Is the behaviour of the meter exactly the same, when held stationary in moving water, as it is when towed through still water? Unless a satisfactory answer can be given to this question, rating curves are valueless. Fortunately the weight of evidence is in favour of the still-water rating tank; among the classic full-scale experiments which proved that the velocity of flowing

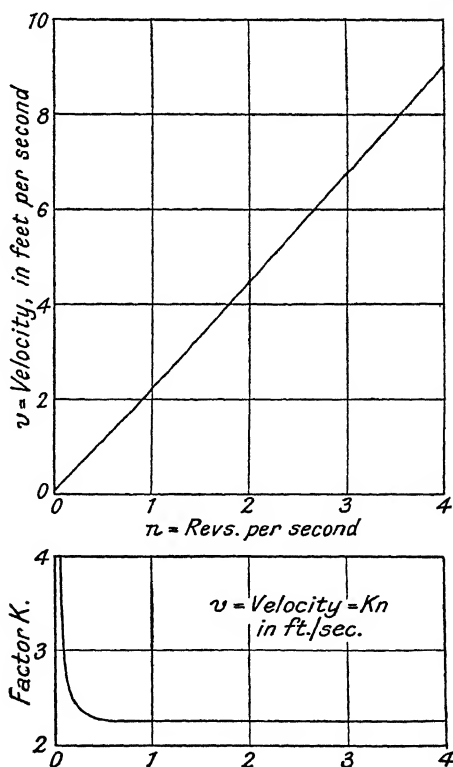


FIG. 51.—Current meter rating curves.

streams, as measured by current meters rated in the normal way, sensibly agreed with the true velocity as determined by absolute methods (§ 79), those at the Assuan Dam ⁽⁴⁷⁾ and at the Walchensee Research Station ⁽⁴⁸⁾ may be quoted.

75. Effect of Oblique Flow. The effects of oblique flow on current-meter registration are much more complex than they are on Pitot tube performance (§ 66), although the general problem is of the same nature—to see how the registration is altered when the current no longer approaches the instrument axially (Fig. 52). It is found that *propeller meters* invariably under-estimate the cosine component of the velocity; that is to say, the velocity computed from the observed speed of rotation of the meter in conjunction with the appropriate

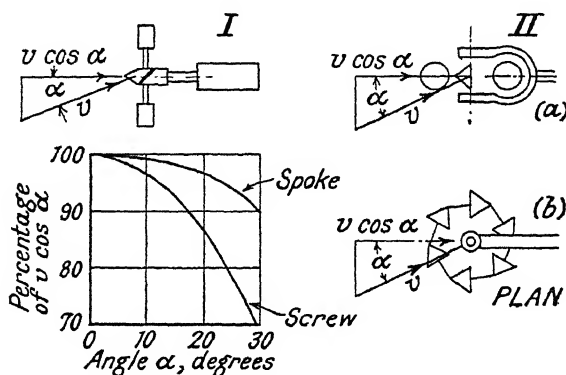


FIG. 52.—Oblique flow on current meters.

rating curve, is always *less* than the true value of $v \cos \alpha$. The discrepancy between the two values: (i) increases as the angle of deviation α increases, (ii) is greatly influenced by the shape and type of the propeller, and (iii) may sometimes be influenced slightly by the magnitude of the velocity. Typical curves showing the relationship between the angle α and the percentage of $v \cos \alpha$ that is actually registered are reproduced in Fig. 52 (I), which shows how much more sensitive to these changes the screw type is than the spoked type (§ 71); indeed, the spoked meter is virtually unaffected until the deviation exceeds 10° .

Example: If the current approaches a screw meter having the characteristics shown in Fig. 52 at an angle of 20° , and the

apparent velocity as deduced from the propeller speed is 3.68 ft /sec., then the true cosine component would be

$$v \cos 20 = \frac{3.68 \times 100}{86} = 4.28 \text{ ft./sec.},$$

and the velocity v would be 4.56 ft./sec.

Oblique flow on *cup* meters can only be discussed if the tail is removed and the meter is rigidly rod-supported, for a cable-supported meter (Fig. 46) would always swing into the direction of the current and the angle of deviation would always be nil. A distinction has to be made, too, between vertical deviation of the flow above and below the plane of the wheel (Fig. 52 (IIa)) and horizontal deviations to the right or left of the meter yoke (IIb); moreover, the interference of the yoke itself may modify the effect of obliquity according as the deviation is from the left hand or from the right hand. As a rule, though not invariably, vertical deviations of the kind typified in Fig. 52 (IIa) cause the cup meter to register *less* than the true cosine component $v \cos \alpha$; but if the angle α is large enough, over-registration may begin. If, for example, the angle is 90° , so that the cosine component is nil, the meter will still continue to revolve slowly.

Apart from the disturbance created by the yoke, it is evident that deviations of the velocity in a horizontal plane (Fig. 52 (IIb)) can have no effect on the speed of rotation of the meter: so long as the magnitude v remains unaltered, the wheel speed will remain the same no matter how the angle α alters. But during these changes in direction the cosine component $v \cos \alpha$ certainly has been changing, and thus as the angle of deviation α increases and $v \cos \alpha$ diminishes, the meter *over-registers* the cosine component by a continually increasing amount.

A combination of vertical and horizontal obliquity may produce quite unpredictable changes in the registration of cup meters, which makes it impossible to establish for these instruments definite relationships such as those recorded in Fig. 52 (I) for propeller meters.

76. Effect of Turbulent Flow. Current meters working in turbulent water—which is to say, in effect, current meters in normal use—are subject to irregularities of flow additional to the fluctuations of velocity in magnitude and direction that

are represented in Fig. 52. Turbulence may be regarded as the effect of the random passage through the whole body of water of eddies, whirls, and vortices. If such a vortex, rotating about a vertical axis, happens to be concentric with the wheel of a cup meter, the wheel will temporarily be accelerated (or retarded), and a similar result will follow the inter-action between a propeller meter and an eddy revolving about a horizontal axis. Expressed in another way, it can be said that the incessant change in resultant magnitude and direction of the velocities of the water filaments impinging on the moving element of the meter will cause different parts of the wheel or screw to be acted upon at the same moment by different influences; and the rapidity with which the wheel speed can adapt itself to the resultant effect of these quickly changing impulses will again depend upon the mechanical inertia of the wheel. Finally, the meter itself may be accused of adding to the confusion from which it is trying to extract orderly information—the cup meter at least has been described with some justification as “a most ingenious instrument for creating turbulence.”

From such complexity there is little hope of drawing consistent statistical conclusions. But general tendencies are definite: many experiments ⁽⁴⁹⁾ in which current meters have been exposed in comparable conditions to artificially created and exaggerated turbulence have shown that as the degree of turbulence increases, cup meters nearly always tend to register a velocity *greater* than the true mean cosine component, while propeller meters register *less* than the cosine component. These results, then, are not inconsistent with what would be expected from a study of the effects of oblique flow (§ 75). It is important to remember, also, that they apply to extreme conditions. The normal degree of turbulence experienced in freely flowing rivers and canals has too small an effect to prevent trustworthy results being obtained with either type of meter; the question of what abnormal amount of turbulence will make accurate velocity measurement impracticable is touched upon in § 158.

77. General Comparisons. Discussion of the relative merits of cup and screw meters forms one of the major controversies of hydraulic engineering. Some of the points that have been advanced on the one side and on the other are—

- (i) The cup meter is more sensitive to disturbances, e.g. its rating is affected more seriously than that of the propeller meter if it is brought close to the side of the channel, if it is not held stationary, and so on.
- (ii) The propeller meter has been used for a higher range of velocities than the cup meter—up to 20-30 ft./sec. as against 10-15 ft./sec.
- (iii) The cup meter offers the greater resistance to the flow of the water, and thus may be swept further downstream than the propeller meter (§ 160).
- (iv) The effective diameter of the propeller meter can be made much less (down to $2\frac{1}{2}$ ins.) than that of the cup meter (about 5 ins.), which gives it an advantage in positions near the walls of pipes where there is a steep velocity gradient (§ 139).
- (v) The cup meter is a more robust instrument than the propeller meter, and can thus be put into relatively unskilled hands.

It will thus be seen that the choice of meter depends mainly on the conditions in which it will be used. For the routine gauging of rivers and canals where cable-suspended meters are employed, the theoretical advantages of the propeller meter seem to be of little practical weight. Officials in control of great organisations responsible for daily river gaugings over extensive territories, whose experience and soundness of judgment are unassailable, say that they find the cup meter reliable and satisfactory, that the more they know about it the more they depend on it, and that until a better meter is produced they intend to keep on using the cup meter. But in other fields more experience has been gained and recorded by users of propeller meters than by exponents of the cup meter, and this preponderance of opinion cannot lightly be set aside by experimenters newly entering these fields.

The degree of accuracy to be expected of current meters is quite evidently not a question on which anyone would care to be dogmatic. Well-trained observers, working under favourable conditions, would claim that their results were not in error by more than ± 1 or 2 per cent., and their critics would hardly expect the errors to exceed 3 to 5 per cent.

CHAPTER VI

MEASUREMENT OF DISCHARGE BY FREE-FLOW APPARATUS

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78. Types of Discharge Measurement. The purpose of discharge measurements is to determine either, (i) the total number of units of weight or volume of liquid flowing past a given point in a specified period of time, or (ii) the number of units flowing past the point in unit time. *Total flow* (i) will be expressed in pounds, gallons, cubic feet, or the like ; while *rate of flow* (ii) will be expressed in cubic feet per second, gallons per minute, millions of gallons per day, or the like.

Because of the very great range of conditions that may be encountered in flow measurement, very varied basic principles are brought into service. In the following chapters the general system adopted has been to classify measuring methods according to conditions rather than according to principle. The present chapter thus describes methods applicable when the liquid issues freely and uniformly, at atmospheric pressure, or nearly so, from the end of a pipe or channel, flowing away at a lower level after passing through the measuring apparatus. Chapters VII, VIII, and IX deal with methods available when the liquid flows under pressure along a closed pipe or conduit, while Chapters X, XI, and XII are devoted to the gauging of rivers, streams, and open channels generally. On the whole, then, successive chapters are concerned with progressively larger quantities of liquid.

In many instances flow-measuring technique involves direct application of the methods and appliances already described in the preceding chapters.

79. Absolute Methods. The gravimetric or volumetric measuring tank (Chap. IV) is the most valuable of all measuring appliances, because it alone enables flow gaugings to be made that depend only on the direct determination of length, weight, and time, and it therefore forms the only primary or absolute standard of measurement. Unless other flow-gauging devices can be compared with and controlled by absolute methods, their indications are always open to doubt.

Details of the construction, calibration and use of measuring receptacles have been given in §§ 56-61; it remains now to discuss the measurement of the time interval t during which the total weight W or the volume Q of liquid is collected. The first question, which determines whether or not an absolute measurement is feasible at all, is the relationship between the time t taken to fill the tank effectively, and the time involved in the switching operation (§ 59). In the simple procedure in which the switching is done by hand and timed by stop-watch, one could not rely on an error of less than $\pm \frac{1}{4}$ sec., so that unless the tank holds at least a minute's supply of liquid there might be an inclusive error of 1 per cent. in computing the rate of discharge. Increasing the size of the tank in the hope of reducing the error brings up the cost rapidly, and it increases also the time taken to run through a series of tests as well as the difficulty of maintaining the requisite uniformity of discharge.

Reassuring though it is to have good big tanks, then, it may often be necessary as well to cut down the limits of error in time measurement. An electrical method must almost certainly be chosen. The one in use in the hydraulic laboratory of Messrs. Electroflo Meters, Ltd.,⁽⁵⁰⁾ depends upon a detecting device embodying a light-sensitive cell; as the stream of water is switched over at the beginning and end of a run it obstructs the ray of light falling on the cell, thus controlling an electrical circuit which starts or stops the stop-watch. Chronographic recording on the principle outlined in § 72 is often preferred, a contact operated by the switching member causing a record to be left on the tape. The interval between

“start” and “stop” is measured by reference to the time signals transmitted by the chronometer and recorded on the tape. Such a system was used in the measuring installation illustrated in Fig. 39 (II), §§ 56, 59.

In flying-start gaugings in which a float gauge is used, it may be practicable to contrive contacts operated by the float scale which could send signals to the tape chronograph.

80. Continuously Operating Measuring Tanks. If an absolute measurement of the total flow throughout a long period is required, two calibrated tanks arranged in parallel must be used, as indicated in Fig. 53 (I), one tank being filled while the other is being emptied, so ensuring that the whole discharge is controlled. The work of opening and closing the

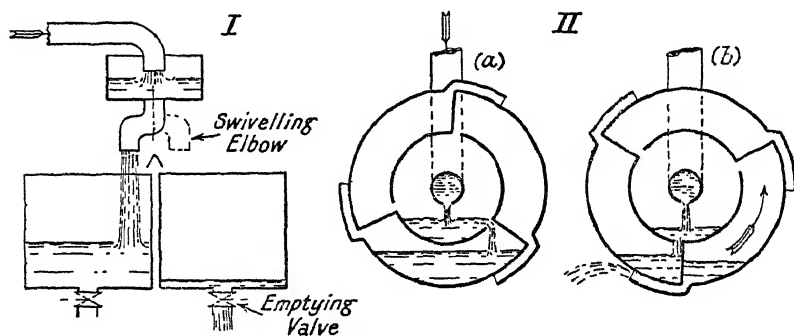


FIG. 53.—Continuously operating measuring tanks.

drain valves, recording the liquid levels or weights, and switching over the swivelling elbow or its equivalent, can, if necessary, be done automatically,⁽⁵¹⁾ thus enabling the total discharge to be registered on the dials of a counter. A further step towards the liquid meter (Chap. VII) is represented by the automatic system of revolving measuring tanks shown in Fig. 53 (II). Three measuring chambers of special shape are arranged so that they can turn about a horizontal axis; liquid enters through a central opening and then through a port into the lowermost chamber. When this is nearly filled the next chamber—the left-hand one in Fig. 53 (IIa)—begins to fill, and as the equilibrium of the whole drum is now destroyed the drum turns to position (IIb), the measured liquid from the first chamber is discharged through an opening in the outer

wall, and the second chamber takes the place of the first. The revolutions of the drum, and therefore the discharge, are shown on a counter. This appliance is sometimes called a *drum meter*.

Other self-recording measuring appliances use tipping measuring vessels which automatically empty themselves when the liquid level reaches a pre-determined height. It is to be noted that in all such systems it is only the total flow that is recorded: to obtain the average rate of flow the elapsed time must be separately observed.

81. Travelling Screen Method. In principle this also is an absolute method, but instead of allowing the water level to rise in the measuring tank, one end of the tank is movable and the discharge is deduced from the speed at which the movable end is pushed along by the incoming liquid. The tank has the form of a long, cement-lined channel whose bed is as nearly as possible level and whose sides are truly plumb, straight, and parallel. On the top of the side walls a pair of

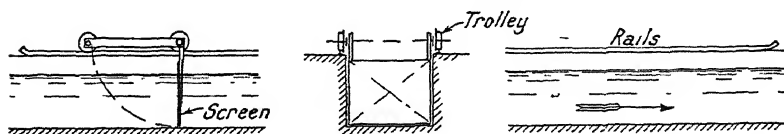


FIG. 54 —Travelling screen.

accurately-levelled rails are laid, forming a track for a light trolley running on ball-bearing axles (Fig. 54), the installation thus closely resembling a current meter rating station; the resemblance extends also to the fixed contacts by the side of the track which, in conjunction with an electric chronograph, permit the speed of the trolley to be exactly known.

The screen itself, built on a light framework pivoted from the trolley about a horizontal axis at right angles to the length of the channel, can either be swung up clear of the water or lowered so that it fits vertically with a very small clearance— $\frac{1}{8}$ in. or less—across the channel. At the beginning of a test the trolley is taken to the upstream end of the track, and when the conditions of flow are stabilised the screen is lowered, so launching the trolley on its run. The chronograph records its speed, and a sensitive level-indicator shows the mean water depth in the channel. Discarding the accelerating and retarding parts of the run, the true mean velocity of the screen is

thus known, and this, multiplied by the effective cross-section of the waterway, gives the required rate of discharge.

The chief uncertainty in the result is stated ⁽⁵²⁾ to be due to the waves on the water surface formed by the immersion of the screen ; to minimise their effect, capillary damping between the tank and the measuring well (§ 48 (ii)) is essential. With this precaution an overall error in the computed rate of discharge of not more than ± 0.2 per cent. has been claimed, representing an accuracy that can rarely be surpassed with a measuring tank. In addition to this high accuracy, the travelling screen method has the advantage that it in no way disturbs the flow and imposes virtually no loss of head—throughout all the preparations and during the test run itself, the water continues to flow uninterruptedly along the channel. Of course a high price has to be paid for these merits—a price beyond the means of any but organised testing institutes, for manifestly the workmanship required in making a channel to the required limits of accuracy must be of an unusually high order, especially when the dimensions are 55 m. long by 2 m. wide by 1.895 m. deep, as in the equipment ⁽⁵³⁾ at the Federal Hydraulic Research Laboratory at Zurich, Switzerland.

82. Orifice Gauging Tanks. Although this method can only be regarded as a secondary standard, ultimately depending for verification on comparison with a measuring tank test, it is very convenient for small discharges. The gauging tank (Fig. 55) should preferably be cylindrical, standing vertically ; in its base is an orifice of specified form, the rate of flow through which can be computed from the head of liquid above it. A plain piezometer tube serves for indicating the head, its scale being graduated directly in units of discharge. A difficulty that arises here is that as the head varies roughly as the square of the discharge, the liquid level becomes low and awkward to read at small flows. It is therefore advantageous to use for very variable flows two or more tanks mounted side by side and connected in parallel, as shown in the diagram, the orifices having areas in the ratio of, say, 1 : 2 : 6 ; then by suitably regulating the inlet valves so as to divert the liquid into whichever combination of tanks gives the greatest heads, an overall range of discharge from 100 per cent. to 5 per cent. can be

gauged with an almost uniform accuracy of perhaps ± 2 per cent.

As the liquid approaching the orifices must be free from eddies, stilling arrangements as suggested in the diagram are necessary, comprising a perforated diffuser on the end of the inlet pipe, and one or more transverse baffles made of gauze or of perforated metal. The alternative plan sketched in Fig. 56 (I) is attractive because it allows the *effective* head to be drawn down quite low when small discharges are being

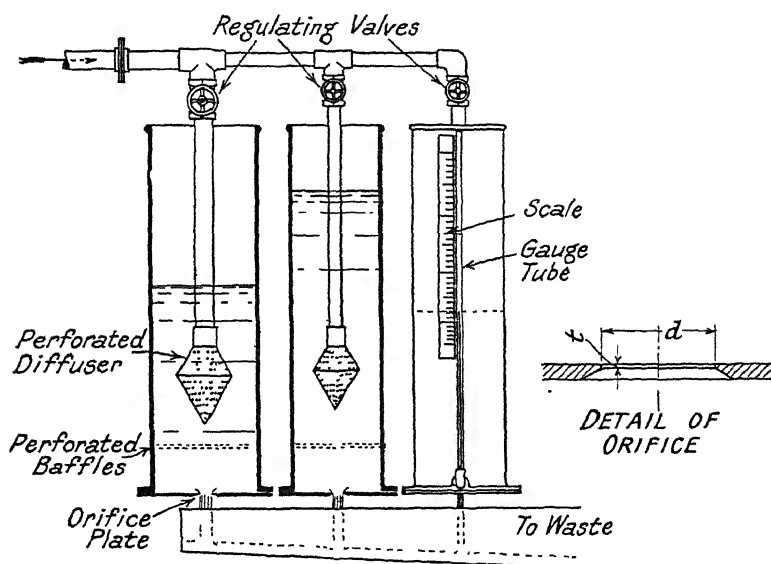


FIG. 55.—Orifice gauging tanks.

measured, while still keeping the tank full, and without the danger of excessive disturbance near the orifice. The additional manipulation required—occasionally sending an excess of liquid into the tank in order to force residual air through the vent—is not very serious. See also Fig. 63.

There is little to be gained by making the cross-section of the tank unduly large in relation to the size of the orifice, for to do so only accentuates one of the troubles inherent in the system shown in Fig. 55—the long time the observer must wait after a change in the rate of flow, which may be a matter of minutes, before the liquid surface again stabilises itself. If

the tank diameter is 8 or 10 times the orifice diameter, this will ensure that the velocity of approach is too small to have any appreciable influence on the gaugings.

83. Calibration of Gauging Tanks. It is most desirable that the graduated scales from which the rate of flow is read should be calibrated by using a standard measuring tank.

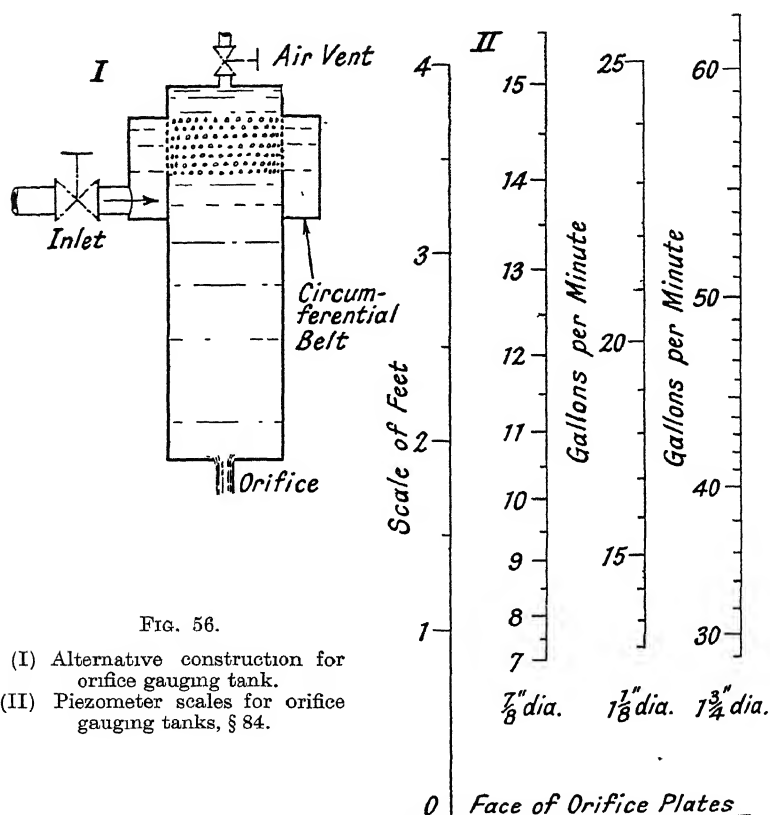


FIG. 56.

- (I) Alternative construction for orifice gauging tank.
 (II) Piezometer scales for orifice gauging tanks, § 84.

Various discharges in succession are allowed to flow through one of the gauging tanks and then into the measuring tank; for each discharge a mark is made on a blank paper scale showing the height of the piezometer column, a graph is plotted between head and discharge, and finally the permanent graduations can be marked on the piezometer scale. These graduations, it should be noted, are valid only for the particular

liquid tested, at the temperature then prevailing. The method of correcting for changes of viscosity if other liquids or other temperatures are involved is explained in *Example* (ii), § 84.

If a measuring tank is not available and the piezometer scales are to be calibrated mathematically with the help of standard orifice formulæ, the first essential is to make the orifice plate itself of standard form. It should be of bronze or stainless steel, perfectly flat, the edge of the orifice should be dead sharp and square, the lower part of the orifice should be relieved as shown in the detail (Fig. 55), and the remaining upper cylindrical length should not have a vertical height t greater than $\frac{3}{32}$ in. The orifice should be set concentrically in relation to the tank, to which the orifice plate forms the flat base. The tapping for the gauge tube should be immediately above the upper surface of the orifice plate.

The discharge formula applicable is

$$q = C_d a \sqrt{2gh} \quad . \quad . \quad . \quad (9)$$

where q = discharge,

C_d = an empirical coefficient of discharge, whose value is independent of the system of units,

a = area of orifice,

g = acceleration of gravity,

h = head above upper surface of orifice plate.

(For notes concerning units see § 3.)

The value of the empirical coefficient C_d depends on the orifice diameter d , the head h , and the kinematic viscosity ν of the liquid, in the manner shown in Fig. 57. The relationship

between C_d and the nominal Reynolds number $R_n = \frac{\sqrt{2gh} \cdot d}{\nu}$

is not sufficiently well-established to permit a single graph to be drawn between them, but for a given value of R_n there is a reasonable probability that the corresponding value of C_d will fall within the hatched zone in the diagram.⁽⁵⁴⁾ It is noteworthy that the range of uncertainty grows wider as the Reynolds number diminishes, which shows that accurate measurements are more likely to be made if the liquid is "thin," if the orifice is large, and if the head is high.

The graduation of the scale of each gauging tank can now proceed thus: Having found the kinematic viscosity ν of the

liquid to be used, at the specified temperature, various values of the nominal Reynolds number can be worked out for the range of heads contemplated, corresponding mean values of the coefficient C_d are taken from Fig. 57, values of q can then be computed from formula (9), and finally the $h - q$ curve is plotted. Interpolation from the plotted points at last yields the scale graduations.

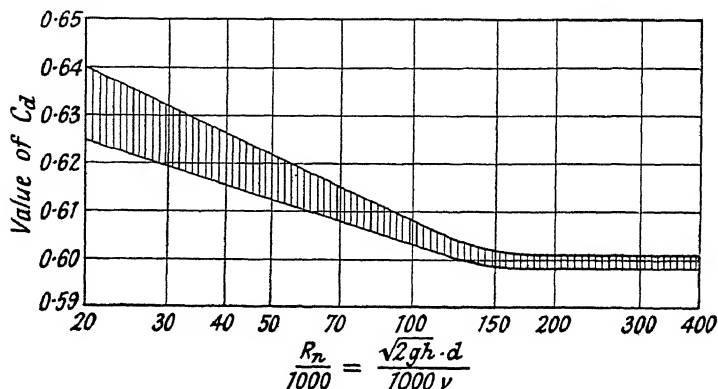


FIG. 57.—Relation between Reynolds number and coefficient for free-flow sharp-edged orifices.

84. Orifice Tank Calculations.

Example (i): A set of 3 orifice gauging tanks is required for measuring water at a temperature of 50° F. The maximum discharge will be 100 gallons per minute, the maximum head will be about 4 ft., the minimum head about 1 ft., and the range of discharge is to be as large as possible. It is required to plot the graduated scales for the piezometer tubes.

Under a head of 4 ft. the discharge of the smallest tank should be

$$100 \times \frac{1}{1 + 2 + 6} = 11.1 \text{ galls./min.}$$

$$= \frac{11.1}{60 \times 6.23} = 0.03 \text{ cu. ft./sec.}$$

Assuming a provisional value of C_d of 0.6, we have, from equation (9), $0.03 = 0.6 \times 0.7854d^2\sqrt{64.4 \times 4}$, from which $d = 0.063$ ft.

Similarly, the diameters of the other two orifices are found to be 0.089 ft. and 0.154 ft. In order to permit standard go-and-not-go limit gauges to be used to ensure accurate machining

of the orifice plates, and in order to have a little overlap between the capacities of the three tanks, it would be preferable to take as the orifice diameters the figures

$$\frac{7}{8} \text{ in.}, 1\frac{1}{8} \text{ in.}, \text{ and } 1\frac{3}{4} \text{ in.}$$

For the smallest orifice the calculations referred to in § 83 are carried out as follows:—

Head $h = 1 \text{ ft.}$

Diameter $d = 0.0729 \text{ ft.}$

Area $a = 0.004175 \text{ sq. ft.}$

Kinematic viscosity of water at 50° F.

$$= \nu = 0.0000140 \text{ sq. ft. /sec.}$$

Nominal Reynolds number

$$= R_n = \frac{\sqrt{64.4 \times 1} \cdot 0.0729}{0.0000140} = 41700.$$

Value of C_d , from Fig. 57, = about 0.619.

Discharge in gallons per minute, from equation (9),

$$= 60 \times 6.23 \times 0.619 \times 0.004175 \sqrt{64.4 \times 1} = 7.75.$$

Similar values are worked out for heads of 1.5 ft., 2 ft., etc., and the process is repeated for the other two orifices, the labour being naturally reduced by collecting all the invariable terms into a single factor. Then from the resulting curves between head and discharge the scales as reproduced in Fig. 56 (II) are drawn. These show that the required conditions are fulfilled, and that the range is from 7 to 100 galls./min.

Note that the best way of securing the necessary dead sharp edge when machining the orifice plates is, after rough-facing the upper surface and finish-boring the hole, to take a very light finishing cut over the face, working from the bore outwards.

Example (ii): What would be the effect on the accuracy of the gauging tanks if the water temperature were to be 100° F. instead of 50° F. ?

The specified change of temperature will reduce the kinematic viscosity of the water from 0.0000140 to 0.0000074. If the discharge is 7.75 galls./min., the Reynolds number will correspondingly increase from 41,700 to 79,000, and the coefficient of discharge will fall from a mean of 0.619 to a mean of 0.609 (Fig. 57). That is to say, for the same reading of the gauge tube, the actual discharge at 100° F. will be about $1\frac{1}{2}$ per cent. *less* than it is at 50° F.

But if the nominal discharge is 60 galls./min., all flowing through the largest orifice, then the rise in Reynolds number from 167,000 to 316,000 will only diminish the true discharge corresponding to a given gauge reading by about 0.1 per cent.

85. Weir Gauging Tanks. In these tanks, as in orifice gauging tanks, the rate of discharge is inferred from observations of head, and they can likewise be of a size that makes them readily portable. The weir gauging tank consists of an open channel or trough built of sheet steel, having vertical parallel sides and a flat horizontal floor. Entering at one end, the water passes first through perforated baffles which damp out eddies, it flows along the channel and then escapes at the other end, in the form of a smooth steady sheet or *nappe*, over the sharp-edged rectangular, triangular, or circular weir (Fig. 58). At a suitable point in the channel means are pro-

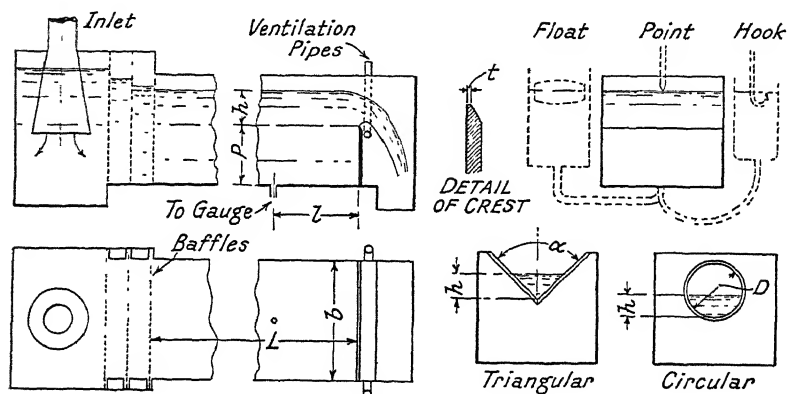


FIG. 58.—Weir gauging tank.

vided for measuring the water level. The chief points that require attention to ensure reasonable accuracy are—

(i) Smooth, undisturbed flow in the channel can be hoped for only by “killing” the energy of the water that issues from the inlet pipe. The flow must therefore certainly enter the tank below the surface level, to avoid splashing and the entraining of air bubbles, and the smaller the entering velocity the less will be the energy to be destroyed. The enlargement of the inlet basin, suggested in Fig. 58, also helps to disperse energy. The baffles may be of perforated metal or of gauze, and the grooves that accommodate them should be sunk flush with the walls and floor of the channel.

(ii) Although ideally the longer the tank the better, because more opportunity is thus given for disturbances in the water

to die out, yet the longer also becomes the time required to attain a steady water level after changes of flow. A reasonable minimum is to let the length L between the downstream baffle and the weir plate be equal to 10 times the maximum head h .

(iii) The distance l between the weir plate and the tapping leading to the head-measuring device should not be less than three times the maximum head h . The requirements laid down in § 43 must be carefully observed.

(iv) The weir plate should be of bronze or stainless steel, accurately finished to the specified shape (§§ 88-90). The edges over which the water flows must be dead sharp and square, the downstream edge must be relieved or bevelled as shown, leaving only a narrow horizontal strip whose width t should not exceed $\frac{1}{16}$ or $\frac{1}{8}$ in.; and the plate must be mounted truly square and plumb across the channel. No projections of any kind are permissible on the upstream face of the plate, which must be quite smooth over its *whole* surface; any screws for attaching the weir plate to a stiffening steel bulkhead must have countersunk heads.

(v) For rectangular weirs the ventilating pipes shown in Fig. 58 are indispensable, their purpose being to make sure that there is always atmospheric pressure beneath the nappe or sheet of falling water. Two pipes 1 in. diameter will serve for discharges up to 3 cu. ft./sec.

(vi) Downstream of the weir plate, if the weir is rectangular, the width of the channel must remain unaltered.

86. Gauging the Head over the Weir. Float, point, and hook gauges (Chap. I) are equally serviceable for measuring the head over the weir, the predominant need being for great accuracy. If the gauging tank is set at about eye-level a hook gauge in a glass gauge well is very convenient. Float gauges do not require any skill in manipulation, the level may be read directly from a circular scale, and it is even possible to graduate the scale in units of discharge.

The establishment of the zero position of the gauge—that is, the position corresponding to zero head when the water surface is level with the weir crest or sill—must be very carefully done. It is quite inadmissible to attempt this by letting the water drain away over the weir until no more runs out, for in this way the still water surface might remain nearly $\frac{1}{8}$ in.

above the crest because of the effect of surface tension. The proper method is sketched in Fig. 59, which shows a cross-section of a tank having a rectangular weir with horizontal crest. Bolted inside the tank, well away from the weir plate, is a small bracket supporting a pointed screw which can be adjusted by the use of lock-nuts and which serves as a fixed reference gauge. The tank being drained, a straight-edge is laid across the weir crest and rests with its other end on the point of the zero reference gauge, which is then carefully adjusted and locked so that a spirit-level indicates that the straight-edge is truly horizontal. After removing the straight-edge and spirit-level, the operator admits water into the

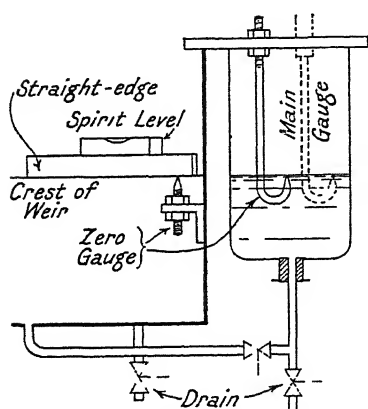


FIG. 59—Zero setting for rectangular weir.

gauging tanks and regulates its level—an operation that may be a little tiresome—until the fixed point of the zero gauge is precisely in the water surface. Then the main gauge, which is here assumed to be a hook gauge, is similarly adjusted until its point also is in the water surface, that is to say, in the horizontal plane containing the weir crest. Finally, the main gauge is read, the reading constituting the *zero reading*. When the tank is in use, the effective

head over the weir is obtained by subtracting from the observed reading the zero reading.

87. Weir Gauging Procedure. So long as the tank is not moved there is no need to re-set the zero gauge except as an occasional check, but the zero reading of the main gauge should frequently be verified by comparison with the zero gauge. To permit this to be done without stopping the flow of water the additional zero gauge suggested in Fig. 59 may be tried; it is fixed in the glass gauge well that houses the main gauge, it is set at the time that the main zero gauge is set, and it is used by closing the isolating cock between the tank and the gauge well and then cautiously opening the drain-cock.

When making the zero setting of triangular weirs it is evident that the straight-edge must have a little triangular foot or pad which fits accurately into the apex of the weir.

During gauging a danger to be kept in mind results from reading the hook gauge before the water level is stabilised. The common-sense precaution is to take two readings in succession, and to make sure that they agree before passing on to the next test.

A more insidious danger affects only the rectangular weir. If a small discharge is being gauged and if the head is built up by gradually opening the inlet valve, a *clinging nappe* may form, the water clinging closely to the downstream face of the weir plate instead of springing clear as represented in Fig. 58. This type of nappe may persist until the head over the crest has reached several inches, whereupon it will suddenly break away and change into the normal free-springing form. At any stage the clinging nappe will instantly break down if the operator rubs his finger just once along the weir crest. While the clinging nappe persists the gauge readings are completely meaningless, because the discharge computed from them may be 10 or 20 per cent. less than the discharge actually flowing over the weir. Judicious location of the ventilating holes will lessen the chance of the formation of clinging nappes, but this does not relieve the observer from the duty of seeing for himself that the proper kind of flow is operating.

88. Calculations for (i) Rectangular Weir. The *suppressed* rectangular weir is the type recommended for gauging tanks, having a straight, truly horizontal edge or crest extending completely across the tank. The discharge is computed from the formula

$$q = C_d \cdot \frac{2}{3} b \sqrt{2g} \cdot h^{\frac{3}{2}} \quad . \quad . \quad . \quad (10)$$

where q = rate of discharge,

h = measured head above weir crest,

b = length of weir crest = width of channel,

C_d = a coefficient of discharge whose value is found from the expression

$$C_d = 0.605 + \frac{1}{320h - 3} + \frac{0.08h}{P} \quad . \quad . \quad . \quad (11)$$

in which h is the head in *feet*,
and P is the height of the weir crest above the floor of
the channel (Fig. 58), expressed in *feet*.

(Note that the basic formula (10) is a general one, while formula (11) requires that *foot* units should be used.)

Formula (11) gives Rehbock's value for the coefficient of discharge, and it should only be accepted in the light of the information given in §§ 177-178. It is valid for water at ordinary temperatures, a range of 20° F. producing no appreciable effect on the value of the coefficient.⁽⁵⁵⁾

Example (i): Determine suitable dimensions for a rectangular weir gauging tank having a maximum capacity of 500 gals. per min.

As a provisional estimate, take $C_d = 0.64$, and let $b = 3h$.

$$\text{Now } 500 \text{ gals./min.} = \frac{500}{60 \times 6.23} = 1.34 \text{ cu. ft./sec.} = q.$$

From formula (10),

$$1.34 = 0.64 \times 0.667 \times 3h \times 8.03 \times h^{\frac{3}{2}}, \text{ or } h = \text{about } 0.45 \text{ ft.}$$

The tank might therefore be 1.5 ft. wide by 6 or 8 ft. long, and a suitable height P would be 1 ft.

Example (ii): When a gauging tank is accurately measured after construction it is found that the crest length is 1.496 ft. and the height P is 1.016 ft. What would be the discharge under a head of 0.302 ft.?

From formula (11),

$$C_d = 0.605 + \frac{1}{320(0.302) - 3} + \frac{0.08 \times 0.302}{1.016} = 0.640,$$

a value which agrees purely fortuitously with the original estimate.

From formula (10),

$$\begin{aligned} q &= 0.640 \times 0.667 \times 1.496 \times 8.03 \times 0.302 \sqrt{0.302} \\ &= 0.852 \text{ cu. ft./sec.} = 318 \text{ gals. per min.} \end{aligned}$$

For routine gaugings with a given rectangular weir the height P and the width b will remain constant, and it is therefore easy to plot a chart from which q can directly be read off. Logarithmically ruled paper is useful, and if it is not available it can readily be improvised by transferring to the axes of the graph the logarithmic graduations on a slide-rule. Such a chart, prepared for the gauging tank referred to in *Example (ii)*,

is reproduced to a reduced scale in Fig. 60. Charts with linear scales are equally satisfactory.

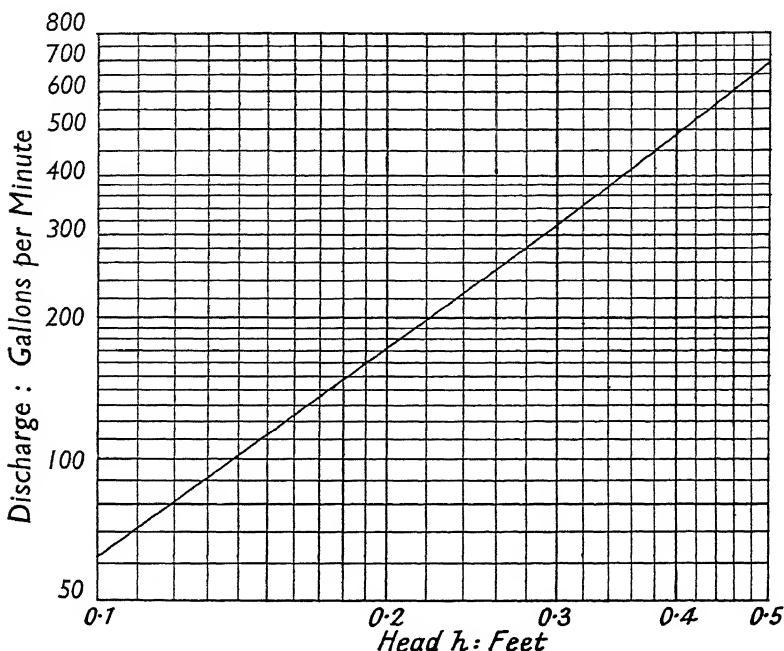


FIG. 60.—Discharge chart for suppressed rectangular weir 1.496 ft. wide and 1.016 ft. high.

89. Calculations for (ii) Triangular Weir. This type of weir, especially when used for small flows, is often called the *V-notch*. Its basic flow formula is

$$q = C_d \cdot \frac{8}{15} \cdot \sqrt{2g} \cdot \tan \frac{\alpha}{2} \cdot h^{\frac{5}{2}} \quad (12)$$

where α is the included angle formed by the two sides (Fig. 58). The value of the coefficient of discharge C_d has an average value of about 0.593, but as it varies to a slight extent with the head it is customary to include the variables in a single exponential term, thus,

$$q = Ch^{2.48} \quad (13)$$

The weir coefficient C has the following *invariable* values :—

Included Angle α	$\tan \frac{\alpha}{2}$	Units in which Head h is Expressed	Units in which Discharge q is Expressed	Value of C .
90°	1.000	Feet	Cu. ft./sec.	2.48
$53^\circ 8'$	0.500	"	"	1.24
27°	0.240	"	"	0.613
90°	1.000	Centimetres	Litres/sec.	0.0147

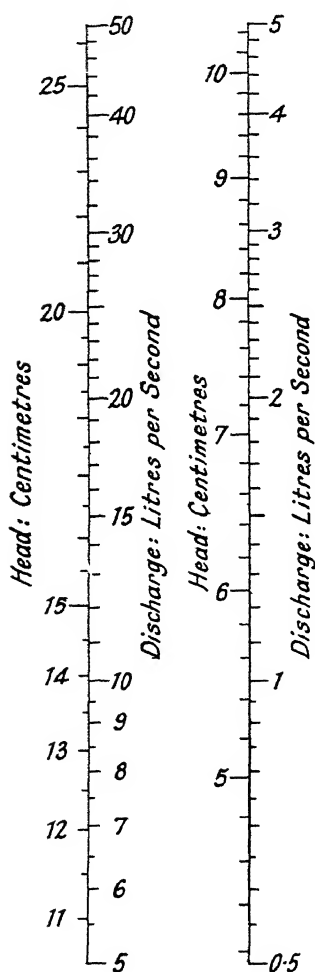


FIG. 61.—Discharge chart for 90° V-notch.

The right-angle or 90° notch is the one most commonly used; the only advantage of choosing a smaller angle is that for a given flow the head is greater and can be measured with less risk of error.⁽⁵⁶⁾ The figures given in the table are valid for water at a temperature of about 50° F., and for gauging-tanks in which the width b is not less than five times the maximum head and the height P to the apex of the notch is not less than twice the maximum head. *Temperature changes* may have an appreciable effect: a drop from 50° F. to 32° F. will probably cause an increase in discharge for a given head of 0.3 per cent,⁽⁵⁷⁾ while a rise from 50° F. to 100° F. may reduce the discharge by 0.8 per cent.

Although it is true that exponential formulæ such as (13) can only be worked out by logarithms, 5-figure tables in this case being preferable, yet on the other hand they are the easiest of all to represent on logarithmic charts, for the graph is a straight line. A method of plotting that some users consider still more convenient is the one shown in Fig. 61. One

set of graduations is marked off direct from the slide-rule, and the other set is enlarged in the ratio 1 : 2.48. In the diagram metric units have been chosen to show how very well they are adapted for the range of values met with in this type of flow ; but exactly the same scales will serve for any V-notch and any units by sliding one scale relatively to the other the necessary amount. Useful tables giving worked-out values of discharges for different heads are also available in the publications of the British Standards Institution.⁽⁵⁸⁾

90. Calculations for (iii) Circular Weir. The head-discharge relationship for the circular weir is so complex that an approximate expression only can be offered : ⁽⁵⁹⁾

$$q = C_d \left[10.12 \left(\frac{h}{d} \right)^{1.975} - 2.66 \left(\frac{h}{d} \right)^{3.78} \right] d^{\frac{3}{2}} \quad (14)$$

Here d is the diameter in *decimetres*, q is the discharge in *litres per second*, and the coefficient of discharge C_d has the value

$$C_d = 0.5550 + \frac{1}{110} \frac{h}{d} + 0.041 \frac{h}{d}.$$

The chief advantage of this weir is that the weir plate can very easily be turned up in the lathe. As against this it has little overload capacity, and consequently if the discharge accidentally becomes excessive the water will overflow from the gauging tank. Nevertheless, if calibration by a measuring tank is practicable it is easy to imagine conditions in which the circular weir might be preferred.

91. Comparative Comments on Flow-gauging Apparatus. (i) *Maximum flow.* The numerical examples have already shown that in general the rectangular weir is fitted for relatively large flows and the orifice for relatively small flows, the triangular weir holding an intermediate position.

(ii) *Range of flow.* Fig. 62 serves as a reminder that a single orifice tank can deal only with a limited range of flows—hardly more than 1 : 2—whereas quite a large range of flows over a V-notch does not produce an inadmissible variation in head. When very varying discharges have to be gauged by weirs, it may be advantageous to have a rectangular weir and

a triangular weir working in parallel, mounted in separate tanks, and arranged so that either or both can be used.

(iii) *Mounting.* The rectangular weir must have its crest truly horizontal, the two sides of a triangular weir must be equally inclined, but the circular weir is subject to no such restrictions.

(iv) *Accuracy.* Because of the respective forms of the head-discharge relationship, an error of 1 per cent. in measuring the head will result in a $\frac{1}{2}$ per cent. error in estimating the

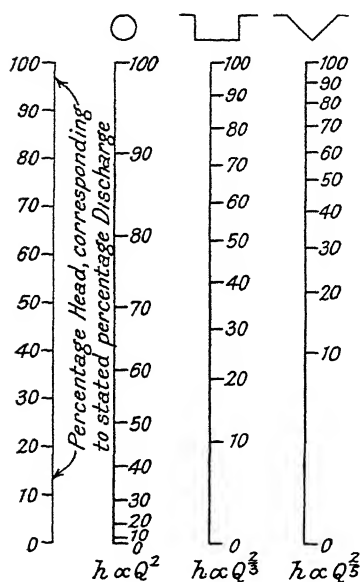


FIG. 62.—Comparative scales for orifice and weirs.

discharge through an orifice, a $1\frac{1}{2}$ per cent. error for a rectangular weir, and a $2\frac{1}{2}$ per cent. error for a triangular weir. Since the head over weirs may be only a few inches, unavoidable errors in measurement, added to the possibility of imperfections in the lay-out of the gauging tanks, make it unjustifiable to guarantee an overall error in computing the discharge of less than ± 2 per cent. When using the Rehbock formula for rectangular weirs the error will almost certainly be a negative one—the computed discharge, if in error at all, will be less than the actual discharge (§ 177).

The rectangular weir is inordinately sensitive to disturbances in the approach channel, so that if such a gauging apparatus is to be calibrated by a measuring tank—a very wise precaution—the arrangement of inlet pipe and baffles during calibration should be *in every respect* identical with the arrangement during routine gauging.

(v) *Intelligent maintenance* is required if gauging tanks are expected to hold their calibration. Baffles act as strainers, and must accordingly be cleaned from time to time, thereafter being replaced *exactly* as they were. Sediment must be cleared

away from the tanks and gauge wells. The edges of the orifices or weir plates must be examined to make sure they are not indented or fouled. If there is a tendency for grease to gather on the weir plate it must be cleaned off with petrol.

92. "Linear" Gauging Tanks. Although the exponential head-discharge relationship $q = kh^n$, on which orifice and weir measurements are based, entails no real difficulty when graphs such as Figs. 56, 60, and 61 are available, yet there are occasions when the possibility of a straight-line relationship is attractive; this would permit discharges to be read from a uniformly-divided scale. Weirs having this characteristic

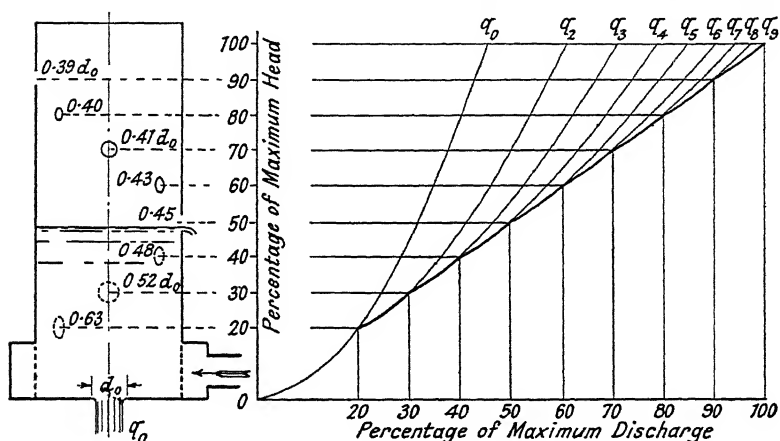


FIG. 63.—Multiple-orifice linear gauging-tank.

might be made, but as they would have a very long crest and acute angles between the crest and the curved sides, practical difficulties may certainly be foreseen. More promising expedients are: (i) to make a cylindrical tank with a number of orifices set at different heights, the orifices coming into operation successively as the discharge increases and the water rises, or (ii) to provide the gauging tank with a circular orifice in the bottom and a very narrow and deep rectangular or trapezoidal weir in the side. Sketches of such appliances are given in Figs. 63 and 64.

Multiple-orifice tank. The trouble here is likely to be that the orifices will discharge under such low heads—sometimes, indeed, acting as weirs—that the values of the discharge

coefficients C_d can hardly be more than guessed at. Because of surface tension, too, there will be a lag with rising surface levels as each orifice comes into play. As regards the step-by-step character of the head-discharge curve, this might not be as serious a difficulty as it looks; one may be justified in believing that with holes proportioned similarly to those in the diagram, the actual departures from the mean curve will not be excessive. The diameters given in the diagram are expressed in terms of the diameter of the hole in the base, assuming an invariable coefficient of discharge.

Combined weir and orifice tank. The method of trial and error is the quickest way of finding out how to make the convex curvature of the weir discharge curve neutralise the concave curvature of the orifice discharge curve, so that the combined

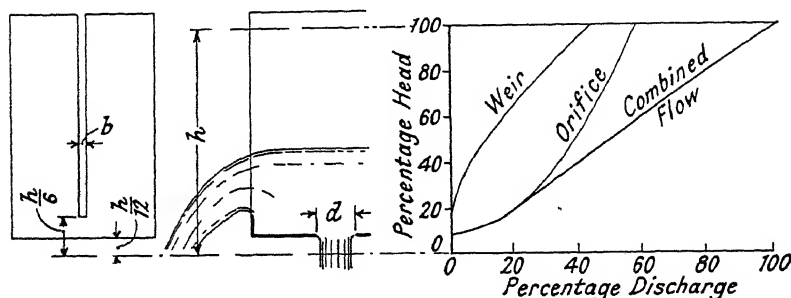


FIG. 64.—Combined weir and orifice gauging-tank.

curve will be a straight line.⁽⁶⁰⁾ The proportions given in Fig. 64, viz. $d = 0.95\sqrt{bh}$, are based on the assumption that the weir and the orifice coefficients are equal and remain unaltered during changes of head; and for a range of discharge of 20 to 100 per cent.—the same as for the multiple-orifice tank—the desired linear head-discharge relationship is satisfied within 1 per cent. To achieve such a result in practice would probably mean opening out the weir into a trapezoidal form, wider at the top than at the bottom.

93. Other Free-flow Measuring Methods.

(i) *Pitot tube.* If the water or other liquid issues straight out of a parallel pipe there is a possibility ⁽⁶¹⁾ that the elementary type of Pitot tube (Fig. 41 (Ib), § 64) could be traversed across the outlet section and the discharge computed as in § 133. A

wide-mouthed nozzle on the end of the pipe would increase the outlet velocity and generate a bigger head in the Pitot tube, and also, by imposing a more uniform velocity distribution on the issuing liquid, it would cut down the number of requisite velocity observations.

(ii) *Standard orifice*. To avoid an inadmissibly large throttling effect, a measuring orifice fixed actually at the end of the pipe must have an area perhaps one-quarter or one-half of the pipe area, and the conditions prevailing in the orifice gauging tank (§§ 82-84) no longer hold good. Comparison must be made instead with the gauging methods described in §§ 114-116. Experiments ⁽⁶²⁾ have shown that the formulæ and coefficients there quoted will apply very nearly to orifices freely discharging into the atmosphere, provided that the necessary stipulations are properly observed. Naturally the head h will now be not a differential head but the head measured at a ring of annular tapplings corresponding to the positive carrier-ring tapping (Fig. 76 (III)).

CHAPTER VII

MEASUREMENT OF DISCHARGE IN CLOSED PIPES

(i) QUANTITY METERS

	§ No.		§ No.
General classification of meters .	94	Inferential meters . . .	101
Range of quantity meters .	95	The vane-wheel meter . . .	102
Considerations influencing choice		The helical meter . . .	103
of meter	96	Combination meters . . .	104
Types of measuring chamber .	97	Meters with recording apparatus	105
Cylindrical-chamber meters .	98	Installation of meters . .	106
Oscillating-piston meter . .	99	Variation in the liquid . .	107
The disc meter	100	Maintenance of meters . .	108

94. General Classification of Meters. Meters are industrial instruments designed to give, without the need for calculation or manipulative skill of any kind, direct information concerning the quantity of liquid flowing under pressure along a pipe-line. The quantity or the rate of flow can be indicated by pointers moving over dials, or it can be recorded automatically on a chart.

Quantity, Total-flow, or Volume meters are those which show the total quantity of liquid, in gallons, cubic feet, or other units of volume, that has passed through the pipe in the interval between two successive readings.

Rate-of-flow meters indicate the instantaneous rate of discharge along the pipe, the units here being gallons per minute, cubic feet per second, or, in general, volume in unit time.

By suitable modification or calculation, either type of meter can be made to give the information the other type is primarily intended to yield. Thus the mean rate of flow passing through a quantity meter is found by dividing the total flow by the elapsed time, while the total volume flowing through a rate-of-

flow meter may be obtained by graphically or mechanically integrating the time-discharge curve.

In this chapter representative types of quantity meter only are described, the next chapter being devoted to rate-of-flow meters.

Quantity meters are subdivided into

(i) *Positive* or *Displacement* meters, in which the record of total flow is based upon counting the number of times that measuring chambers of known volume are successively filled and emptied.

(ii) *Inferential* meters, in which the revolutions of a rotating element acted upon by the flowing liquid are counted.

95. Range of Utility of Quantity Meters. Of the total range of flows that meters in general are required to cover, quantity meters are suitable for the lower end of the scale, which can be said in the broadest terms to include discharges from $\frac{1}{2}$ to 2000 gallons per minute (4 c.c./sec. to 150 lit./sec.); and as one approaches the upper limit of this particular range, it becomes increasingly likely that the inferential meter will be the more appropriate. Because of their construction, which nearly always involves rubbing contact of some element against the walls of the measuring chamber, positive meters as a rule can only accept clean non-corrosive liquids free from grit and suspended solids, and although inferential meters are not so fastidious in this respect they are not really intended for dirty liquids.

Great variations of viscosity do not trouble positive meters—they will handle liquids ranging from petrol and spirits to thick oils (up to 6000 secs. Redwood No. 1) and semi-greases (§ 107). They therefore show to great advantage in measuring bulk supplies of liquid fuel and of lubricants, enabling the quantity pumped into or drawn from storage tanks to be registered nearly as accurately as can be done by actual volumetric gauging of the tank itself (§§ 56-57). By choosing suitable materials for the working parts, positive meters can be made equally serviceable for handling milk, syrups, fruit-juices and other liquid foodstuffs.

Inferential meters are rarely used for liquids thicker than Diesel oil or transformer oil, and their principal field is the metering of cold and hot water.

96. Considerations Influencing Choice of Meter. Some further matters to be weighed when selecting a meter for a given duty are—

(i) The *accuracy* of registration both when the meter is new and after a period of service. In comparable conditions the positive meter should have smaller errors than the inferential meter—errors often not greater than ± 0.3 per cent.; but supervision and maintenance of a high order may be needed to uphold this standard.

(ii) The *minimum flow* at which registration begins. Because of friction and leakage there is a minimum discharge below which the meter ceases to register—the liquid oozes past without causing any movement of the revolving elements. Here also positive meters have the advantage.

(iii) The means for correcting the *registration* of the meter when, because of wear or for other reasons, the error passes permissible limits. In positive meters this can be done either by adjusting the effective volume of the measuring chambers or by altering the ratio between the number of strokes and the number of counter revolutions. In inferential meters the relative speed of the vane-wheel can be adjusted.

(iv) The *loss of head* imposed on the liquid; this may affect the position of the meter, and in the case of pumped supplies it represents a direct waste of power. The loss varies roughly as the square of the discharge, and may be expressed in terms of the velocity head of liquid thus:—

If v = the nominal velocity of the liquid at the inlet flange of the meter,

h_l = the head loss created by the meter

= difference between head at inlet and head at outlet.

K = a factor depending on the type and size of meter,

then $h_l = K \cdot \frac{v^2}{2g}$.

The value of the factor K may range from 1.0 or less for the helical type of inferential meter, up to 20 or more for some types of positive meter; but it should be remembered that the strainer embodied in many positive meters is responsible for a good deal of the loss.

(v) The type of *registering dials*. There may be (a) separate dials, each with its own pointer, showing tens, hundreds, and

thousands, etc., of units of volume (Fig. 65 (I) or Fig. 70); (b) larger dials, with one pointer registering units and a smaller concentric pointer registering multiples, corresponding to the minute and hour hands of a clock (Fig. 67); (c) straight-reading or cyclometer figures, showing units of volume in the same way that an automobile speedometer registers miles or kilometres (Fig. 65 (II)); (d) a combination of these systems; of possible combinations, the clock-face (b) for units and the cyclometer (c) for multiples is very convenient (Fig. 66).

(vi) Whether the dial is “wet” or “dry.” Meters having “wet” gearing and dials are suitable only for filtered water or other innocuous and transparent liquids, for the whole of the reduction gearing, pointers, etc., are immersed, and the final boundary of the liquid is the glass cover protecting the dials.

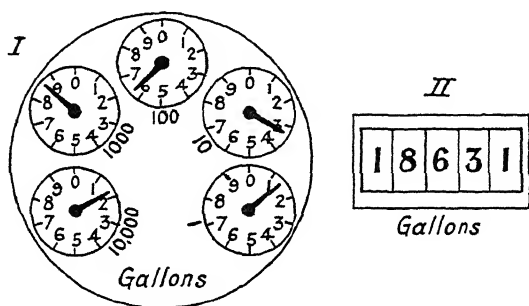


FIG. 65.—Registering systems for quantity meters.

In “dry” dials there is a diaphragm separating the first set of gears working in the liquid from the final set which operate the pointers, and there must therefore be a packed gland or its equivalent to prevent leakage at the point where the spindle passes through the diaphragm (Figs. 68, 70, 71).

For other comparative comments, see §§ 109 and 111.

POSITIVE METERS

97. Types of Measuring Chamber. The fundamental element of the positive meter is its measuring chamber or set of measuring chambers. In the free-flow drum meter illustrated in Fig. 53 (II), § 80, there were no rubbing contacts, and it was not therefore essential to make the chambers of a simple

geometrical form—advantages which allowed the chambers, if necessary, to be of acid-resisting material capable of holding corrosive liquids. But the normal type of meter as installed in closed pipes has a piston or the like, which fits closely against the walls of the measuring chamber and which is pushed forward by the flowing liquid; and there is a limited number of simple geometrical shapes of chamber which can be machined to the requisite fine limits. Of these the cylinder is manifestly the most desirable, and because it enables some kind of seal or

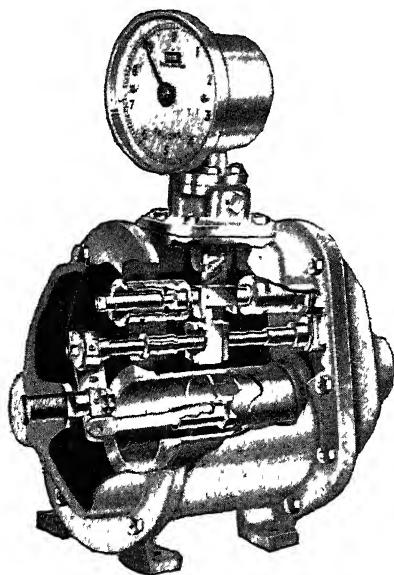


FIG. 66.—Single-cylinder positive meter.

packing to be provided between the piston and the cylinder wall the cylindrical measuring chamber is embodied in meters having the highest claim to accuracy. Other popular forms of measuring chamber, as used in the oscillating-piston meter and the disc meter, are also described in the following paragraphs.

These by no means exhaust the possibilities, though. A meter that can here only be mentioned comprises a pair of oval gear-wheels working against semi-cylindrical surfaces in the manner of a Root's blower, and in another—the rotary

sliding-vane meter⁽⁶³⁾—retractable vanes sweep through the annular space between an inner and an outer cylindrical surface.

98. Examples of Cylindrical-chamber Meters.

(i) *Single-cylinder.* The example shown in section in Fig. 66 is made by Messrs. Precision Meters, Ltd.,⁽⁶⁴⁾ and is suitable for fuel and lubricating oils, etc. A centrally placed valve controls the flow of liquid to and from the measuring chamber, in which a double-acting piston works at a maximum speed of about 110 double strokes per minute; at the end of each stroke the piston actuates the valve through the medium of a

rocker arm and so reverses the flow. The counting mechanism registers gallons and fractions by means of a pointer moving over a large circular scale, and multiples of gallons by straight-reading figures. The calibration can be adjusted by altering the effective length of the stroke, which is done by screwing in or out the rocker-arm pivot seen on the left of the illustration.

(ii) *Four-cylinder.* The meter made by Messrs. Tecalemit, Ltd., and illustrated in Fig. 67, has four radially-disposed cylinders, each opposed pair of pistons being coupled by a Scotch yoke type of connecting-rod which applies a steady torque to the vertical crankshaft. The crankshaft drives (i) a rotary disc valve which distributes the liquid to the four cylinders in turn, and (ii) the counter mechanism which is mounted above the meter; at maximum discharge the crankshaft speed does not greatly exceed 100 revs. per min. Calibration is adjusted either by regulating the stroke-limiting stops in the cylinder heads, or by altering very slightly the gear ratio between the crankshaft speed and the counter speed. Special features which virtually eliminate leakage are the spring-backed cup leathers for the pistons, and the spring-loaded bellows-type seal above the rotary valve.⁽⁶⁵⁾

When passing 100 gallons of water or light oil per minute, a 3-in. Tecalemit meter will impose a loss of head of about 12 ft.

(iii) *Duplex double-acting two-cylinder.* The Brodie meter is an American design having two double-acting cylinders set side by side, and the pistons are interconnected by a train of gears so as to have a 90° phase angle just as the four-cylinder meter has. The connections impart a rotary as well as a reciprocating motion to the pistons, which are so shaped as to uncover inlet and outlet ports pierced in the cylinder walls, no other distributing device being required. The meter is thus distinguished by a very small loss of head.

(iv) *Other multiple-cylinder meters* In another advantageous and compact disposition of multiple cylindrical measuring-chambers, their horizontal axes are equally spaced around the horizontal axis of the meter. A wobble-plate mechanism may be used to give a combined rotary and reciprocating motion to the pistons, thus rendering valves unnecessary. Small instruments⁽⁶⁴⁾ of this type, having either

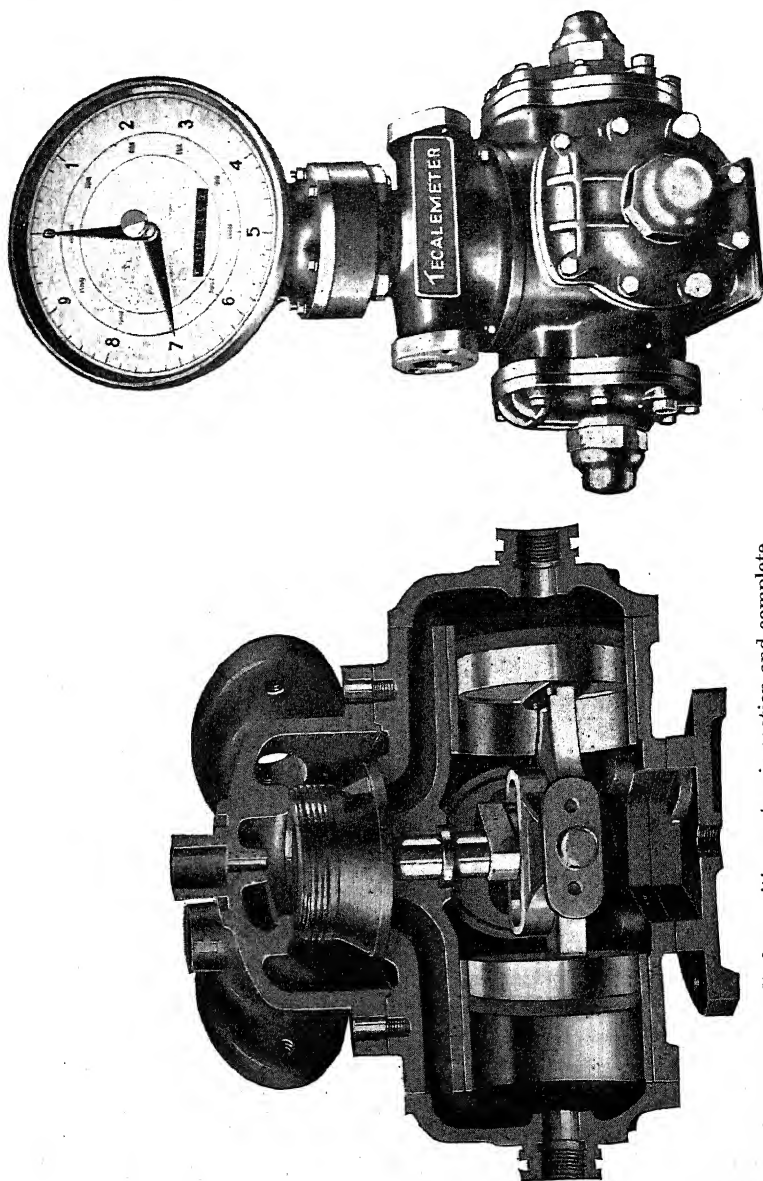


FIG. 67.—Four-cylinder positive meter, in section and complete.

four or five cylinders. and specially adapted for dispensing lubricating and gear oil in garages and air-ports, are made by Messrs. Precision Meters, Ltd.

99. Oscillating-piston Meter. This type of meter, sometimes called rather inaccurately the rotary-piston meter, is specially suited for measuring small supplies of water, e.g. for

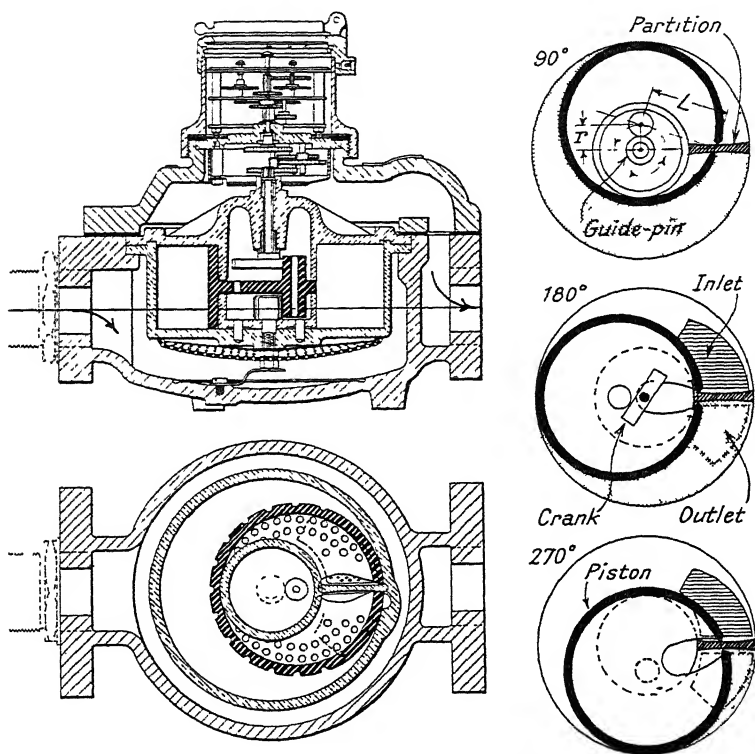


FIG. 68 —Oscillating-piston meter.

domestic purposes, flowing in pipes from $\frac{1}{2}$ -in. to 3-in. diameter. Oil, spirits, and petrol; milk, fruit-juices are other liquids that can be handled by properly constructed oscillating-piston meters.

Fig. 68 shows the details of a meter made by Messrs. George Kent, Ltd. The cylindrical measuring chamber is set with its axis vertical, its length or height being about one-half the diameter. The piston diameter is approximately $\frac{3}{4}$ of the

cylinder bore; the piston is of annular form having a horizontal diaphragm, a central boss, and a vertical slot which engages with a vertical radial partition fixed across the measuring chamber. A guide pin set centrally in the cylinder serves as a roller path around which the lower boss of the piston can turn, sun-and-planet fashion, in an orbit of radius r . Thus constrained, the motion of the piston is identical with the motion of the big-end of an engine connecting-rod of length L (where L is the radius of the meter piston), working on a crank whose throw is r .

Entering the meter body through the inlet flange on the left (Fig. 68), the liquid passes first through a strainer and then flows upwards through a port in the lower end of the measuring cylinder—this port is shown by hatching in the plan views. A corresponding port in the upper end of the chamber, but on the opposite side of the partition, leads the liquid away and allows it finally to escape through the outlet flange. It is to be noted that although the liquid has free access to the inside of the piston, the net or effective flow through this part of the meter is zero because of the inner concentric wall of the measuring cylinder which acts as a seal.

The view of the piston in the general plan of the meter, and the three diagrams showing the position of the piston after its axis has traversed 90° , 180° , and 270° of its orbit, together give a clear impression of the way in which the liquid entering the chamber pushes the piston in front of it and so makes more and more room for itself in the space between the piston and the cylinder. Meantime an equivalent amount of liquid is being forced out of the outlet port, until at the completion of the cycle a volume nearly proportional to the difference between the cylinder cross-section and the piston cross-section has been swept through. Simultaneously, also, the upper boss of the piston has been turning a spindle which, through the medium of a train of gears, has been advancing the pointers of the registering dials the appropriate amount.

100. The Disc Meter. In many ways the disc meter is a close relation of the oscillating-piston meter; it covers much the same field of utility with the same characteristics, its very interesting geometrical construction requires disproportionate space to explain, and its title is not a very closely fitting one.

Sometimes the meter is called the *nutating-disc* meter, but mathematicians say that the term *nutating* is here wrongly applied, and that they know of no term which does accurately describe the motion of the moving element of the meter.

Roughly speaking, the disc wobbles; but whereas a wobbling wheel also revolves, the disc does not revolve. The diagrams (Fig. 69) show that the sides of the measuring chamber are spherical, and the top and bottom are conical with central spherical recesses. The flat disc itself, which serves as a piston, has its outer rim machined to spherical form also, to fit with a

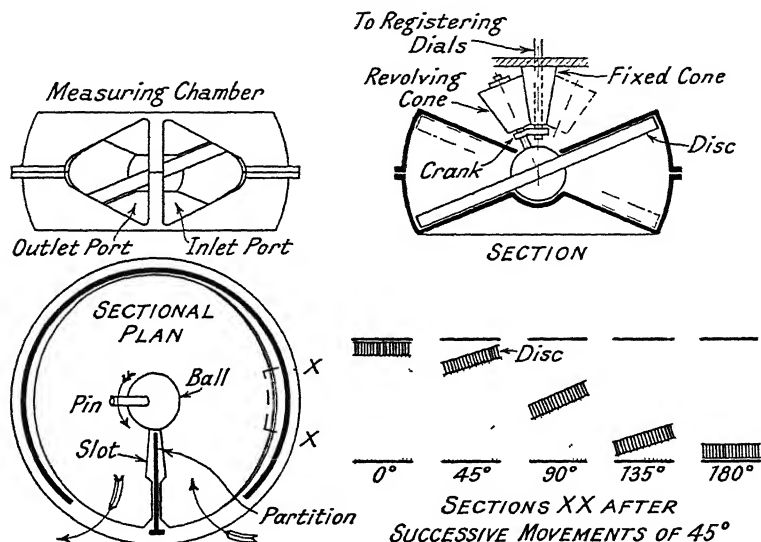


FIG. 69.—Disc meter.

small clearance against the chamber walls, and it has central spherical projections corresponding to the recesses in the floor and roof; an axial pin carries a revolving conical roller which engages with a fixed guide cone set centrally in the main casing. A vertical radial partition across the measuring chamber passes through a radial slot in the disc; on one side of this partition the inlet port is cut through the wall of the measuring chamber, while on the opposite side is the outlet port.

The wobbling motion that ensues when liquid enters the chamber can be followed by reference to the views showing the successive positions of the part XX of the disc. When the

disc has the setting represented in the main views, the element *XX* is at the top of its travel, but each movement of 45° at the same time tilts the element and lowers it too, thus displacing the wedge of liquid below it and forcing the liquid through the outlet port. As the disc itself does not revolve, the degrees of turning movement are those of the spindle, operating the registering pointers, which is caused to turn by a little crank engaging with the diametral pin of the disc. The displacement volume per revolution is very nearly the volume of the measuring chamber minus the volume of the disc.

INFERENTIAL METERS

101. Characteristics of Inferential Meters. The chief advantage of the inferential meter over the positive meter is that as it does not depend upon the filling and emptying of accurately-machined measuring chambers there is no need for the fine clearances that are indispensable in the positive meter, and consequently more latitude can be allowed in measuring slightly impure liquids. Another valuable characteristic is that in the larger types of inferential meter, the head loss is very small and almost negligible—hardly more than a few inches—the factor *K* (§ 96, iv) being less than unity. Again, while inferential meters for large flows are exceedingly compact and may have a bore smaller than that of the pipe itself, positive meters become relatively clumsy and bulky in proportion to the pipe size as the discharge increases, and of course correspondingly costly.

Against these merits, as already pointed out, have to be set these unfavourable factors :—

- (i) Inferential meters are quite unsuitable for very viscous liquids.
- (ii) Even when measuring relatively thin liquids the calibration may be slightly affected by changes of viscosity.
- (iii) The average error throughout the whole measuring range is likely to be greater than with a good positive meter.
- (iv) Under comparable conditions the inferential meter cannot measure very small flows so well as the positive meter.

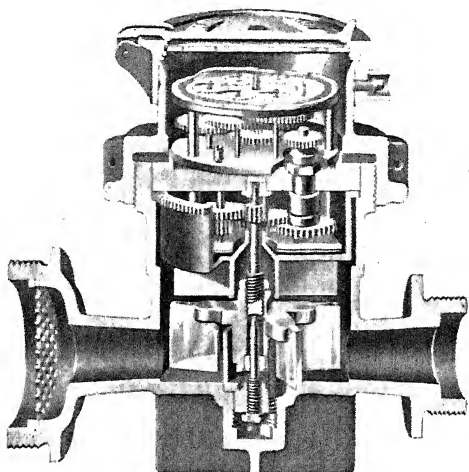


FIG. 70.—Vane-wheel meter.

[See page 123.]

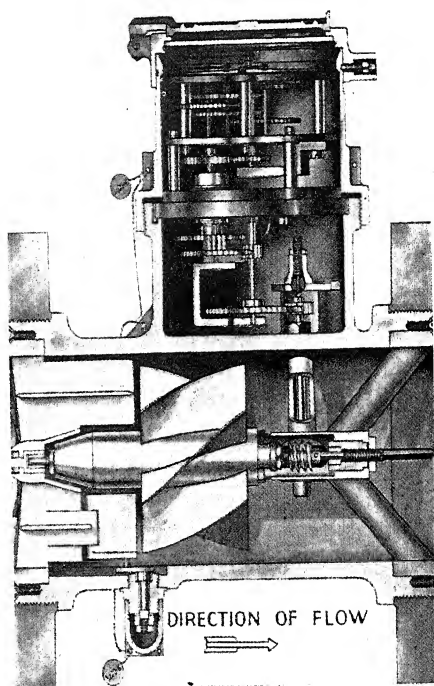


FIG. 71.—Helical meter. (The Leeds Meter Co. Ltd.)
[To face page 123.]

102. The Vane-wheel Meter. A typical vane-wheel meter, as made by the Leeds Meter Co., Ltd., is illustrated in the sectional view, Fig. 70. The liquid passes through it almost in a direct line from left to right, and on its way it impinges on the radial blades of a rotating, celluloid vane-wheel, whose speed is thus very nearly proportional to the speed of the liquid. The photograph clearly shows the wet gearing which considerably reduces the rate of revolution, then the spindle in its packed gland which passes through the watertight diaphragm, and finally the dry gearing which drives the registering pointers.

Calibration is adjusted by regulating the angular position of the two stationary vanes that may be noticed just above the revolving vanes.

Vane-wheel meters are specifically designed for metering domestic water supplies, and they are therefore usually built in small sizes, say for 1-in. pipes; but they are equally serviceable for discharges up to 100 galls. per min. in 3-in. pipes. Designs are available in which the mechanism will suffer no damage if the water in the meter freezes.

103. The Helical Meter. The range of utility of this meter—known on the Continent as the Woltmann meter—is complementary to that of the vane-wheel type; suitable for flows up to 2000 galls. per minute, it can be supplied for pipe sizes between 3 ins. and about 16 ins. Referring to the sectional view (Fig. 71) it is seen that the liquid has a virtually clear passage through a cylindrical body. At the inlet (left-hand) end there is a grid of straightening vanes designed to guide the liquid in a parallel and uniform stream on to the helical vanes of the celluloid revolving element or rotor, which is mounted in bearings fore and aft, and which revolves at a speed proportional to the rate of discharge. A worm and worm-wheel communicate this motion to the pure nickel pinions and wheels of the wet gearing and then to the dry gearing, until finally it is registered on the dials in terms of gallons, cubic feet, etc. One vane of the inlet grid is pivoted so that by means of the device seen in the bottom of the casing the angle of the blade can be adjusted slightly and the calibration accordingly corrected.

Interesting tendencies are recorded in Fig. 72, which gives the performance of a 6-in. helical meter. The very small loss

of head is especially to be noted ; and in regard to the error curve it may be said that it is typical of all inferential meters, showing a maximum positive error just before the curve falls right away into the zone where the discharge is too small to be properly registered at all.

Because of its accommodating nature, the helical meter is

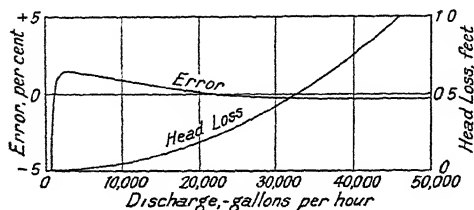


FIG. 72.—Performance of 6-inch helical meter.

one of the most useful general-purpose meters there is. It can be set in any position — horizontal, inclined, or vertical—it is not unduly exacting about the kind of pipe-line in which it is installed, and although its accuracy is not exceptionally high it can keep such as it has in a remarkable way ; after a dozen years' service without any attention whatever, such meters may give exactly the same registration as when first installed.

104. Combination Meters. The inability of the inferential meter to detect small flows below about $\frac{1}{20}$ of its normal

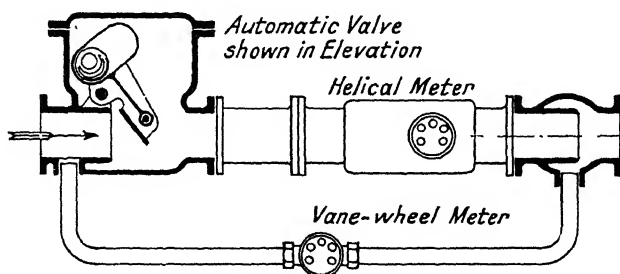


FIG. 73.—Combination meter.

maximum discharge can be remedied by using two meters in parallel, in the manner illustrated in Fig. 73, where a helical meter is interposed in the main pipe and a much smaller vane-wheel meter in the by-pass. So long as the flow is small the automatic valve at the inlet end remains closed and diverts the whole discharge through the vane-wheel meter ; but as soon as the flow exceeds the maximum range of the small meter

the automatic valve opens quickly and fully, so bringing the large helical meter into operation. In this way the combination will still register within usual limits of accuracy even when the minimum flow is only perhaps $\frac{1}{30}$ of the maximum.

The system shown necessitates the reading of two dials and the arithmetical addition of the two registrations, but it is quite practicable to have the two meters mounted in a single casing and showing the total combined flow on a single dial. Another arrangement involves the use of two identical meters ⁽⁶⁶⁾ with an automatic throw-over valve which connects the meters in series for small flows and in parallel for large flows.

RECORDING METERS

105. Meters with Recording Apparatus. Unless an observer stands by the side of a quantity meter of any kind and periodically notes the readings of the dials, it is impossible to tell at the end of a day's run whether the liquid has been flowing uniformly or whether it all went through in a single half-hour. To provide a record of such variations of flow, a clockwork-driven chart can be incorporated in many types of meter, the recording pen being geared to the registering mechanism so that it advances proportionally to the total flow. In the resulting automatically plotted graph, total discharge is plotted against time, so that from the variations of slope an impression can be formed of the corresponding variations of rate of discharge.

INSTALLATION, OPERATION, AND MAINTENANCE OF QUANTITY METERS

106. Installation of Meters. *Positive* meters have the advantage that they are wholly insensitive to velocity disturbances in the incoming liquid, and therefore the presence in the pipe-line upstream of the meter of bends, valves, or irregularities of any kind will in no way affect the registration.

Inferential meters, and especially helical meters, require rather more consideration in this respect. The liquid should approach the helical meter axially along a straight pipe whose bore, at the flange which is bolted to the inlet flange of the meter, is the same as the meter bore. But the pipe need not be parallel ;

in fact very frequently the inlet pipe is a taper reducing-piece to suit the smaller diameter of the meter as compared with the main pipe diameter. That these precautions, if need be, can sometimes be ignored with impunity is shown by the following results of tests: A sluice valve bolted directly to the *outlet* flange of a helical meter was closed about three-quarters of its total travel, creating a head-drop of 80 ft., without sensibly affecting the meter registration. When bolted to the *inlet* flange the valve could be half-closed before the accuracy of the meter, at low rates of discharge, began to fall away. Naturally such acrobatics should not be expected of meters in normal use.

The one essential in the pipe lay-out is that the inferential meter should always be flooded. This means that the meter

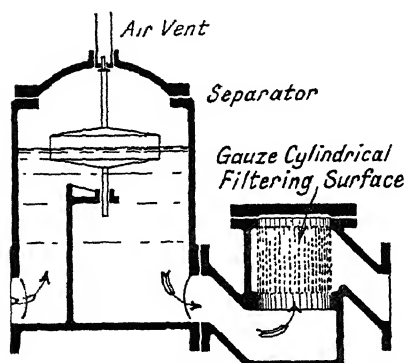


FIG 74.—Separator and filter.

must work under a slight positive head, which can be ensured, even if the outlet pipe discharges freely into the atmosphere, by setting the meter a foot or two below the outlet.

A danger from which all positive meters and some inferential meters must be shielded is damage by dirt or grit carried in suspension by the metered liquid. Before the measur-

ing chamber is fitted in place the pipe-line should accordingly be blown out or flushed to clear away accumulations of solids; then during use the liquid must always pass through a filter before entering the meter. Such filters made of perforated metal are seen in Figs. 68 and 70 actually in position in the meter body; or a gauze filtering surface may be arranged in a separate casing interposed in the pipe-line immediately in front of the meter (Fig. 74)—a preferable alternative for large units because it permits a relatively bigger and a more easily cleaned filtering area, offering at the same time only a moderate resistance to flow.

Separators are often indispensable for the purpose of freeing the liquid of entrained air and vapour before it enters the

meter ; unless this is done the meter would register more than the true amount of liquid passing. If considerable quantities of air and vapour are expected, which often happens during the metering of petrol and similar volatile liquids, a float-operated valve in the upper part of the separator must be provided for venting the vapour (Fig. 74); the vapour if desired may be by-passed to the downstream side of the meter or returned to the air space of the storage tank.

107. Effect of Changes in the Liquid Metered.

(i) *Variations in temperature of a specified liquid.* During its ordinary duty while metering one kind of liquid it is possible that the registration of a meter may be vitiated by changes either of viscosity or of density of the liquid, both such changes being under the influence of temperature. At least with positive meters there is little likelihood that these influences will have any significant effect, and although inferential meters tend to read high as the viscosity rises, the error may not be important. But although the meter may always show the total *volume* of liquid that has flowed through it, the information may not have a precise meaning unless a continuous record of temperature is also available; for temperature changes between limits often encountered in normal operation may alter the density so much that the total *weight* of liquid equivalent to a given volumetric meter registration may vary by 1 or 2 per cent. or more. For this reason some types of positive meter, e.g. the one shown in Fig. 67, § 98 (ii), can be fitted with a thermostatic compensating device which automatically corrects the registration to suit the temperature of the liquid passing through the meter. The readings are therefore always strictly proportional to the weight of liquid.⁽⁶⁷⁾

(ii) *Variations in the nature of the liquid.* An important practical question is whether or not it is permissible to use a meter for a liquid different from the one used in its calibration. One aspect of the question concerns the effect of the liquid on the working parts of the meter ; while, for example, vulcanite or celluloid may perfectly well be used for the rotors or the oscillating pistons of cold-water meters, they would be quite unsuitable for hot water.

As regards the effect on the calibration of wide variations of viscosity resulting from a change of liquid, it may be said that

various types of quantity meter become more and more sensitive in the relative order in which they have been treated in the preceding paragraphs ; that is, reciprocating-piston meters with packed pistons are quite insensitive to viscosity changes over a wide range, disc meters may undergo a slight change—an increase in registration of perhaps 1 per cent. for a tenfold increase in viscosity—while helical meters may require a large correction to compensate for large variations of viscosity. If the Reynolds number of the flow falls below 1000, such helical meters may be subject to a positive error of 13 per cent. as compared with the calibration with water.⁽⁶⁸⁾ In general, a notable increase in viscosity causes a helical meter to over-register and also tends to reduce the measuring range, from which it is clear that these meters should be calibrated with the actual liquid that will flow through them in service.

108. Maintenance of Quantity Meters. In all types of quantity meters there are working parts constantly in motion ; in nearly all types of positive meter the accuracy of registration depends on the maintenance of fine clearances ; so that no meter can be expected to give continuous good service unless it is examined and kept in proper trim according to a pre-arranged schedule, which ideally includes provision for recalibrating each meter as well as for replacing worn parts.⁽⁶⁹⁾ An elaborate organisation is required when, in cities where general metering of house water is stipulated, many thousands of meters are kept working over a large district. One section of the organisation attends to the removal of each worn meter and its replacement by a repaired one ; another tests the meters, still a third puts in the replace parts, and there must also be a comprehensive record department.

Yet a newly planned scheme must be a flexible one, because it is impossible to foresee what particular troubles will be most prevalent with a particular type of meter and a particular quality of water. One supply company may be afflicted with continual complaints of corroded counter gears, another may have complaints of leaky stuffing boxes between the wet and the dry gearing, and so on. The practice in one American city is to take every meter out for inspection and readjustment once in five years, yet the final rejection and complete replacement of meters may not be required until they have given

forty years' service. In North African cities using vane-wheel meters it is found that on the average not more than 2 per cent. of the total number of meters are at any one time out of action for recalibration.

The equipment of the central depot where overhauls are conducted will naturally vary with the number of meters to be handled. The essential item is a calibrated measuring tank into which the flow through the meter can be diverted both before and after repair; then washing tanks are required for cleaning small components, also oil reservoirs in which the counter gears may be dipped, work-benches, and full supplies of spares. Quick-release clamps instead of screwed unions will improve the rate of testing, and there is no objection to testing a number of meters in series instead of individually.

CHAPTER VIII

MEASUREMENT OF DISCHARGE IN CLOSED PIPES

(ii) RATE-OF-FLOW METERS

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Characteristics of differential-head meters	111	Other forms of Venturi passage	124
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109. Limitations of Quantity Meters. To understand the need for the entire new range of metering appliances now to be described, the limitations of the quantity meter must be re-stated. In spite of the excellent features which often give this instrument undisputed control over certain spheres of flow measurement, it is wholly debarred from other fields because of three disabilities :—

- (i) It cannot be economically used for flows greater than about 1500-2000 gallons per minute because of its disproportionate cost and bulk.
- (ii) It would rapidly be damaged and put out of action if dirty liquids were allowed to flow through it.
- (iii) It cannot indicate and record the instantaneous rate of discharge.

This third point will now be developed in detail. As already explained (§ 94), a quantity meter *will* give quite an accurate measure of average rate of flow if a long enough period—say two or three minutes—is available in which to make a timed run, and to compute the value of the difference between the two meter readings divided by the elapsed time. Or if a recording apparatus is fitted (§ 105), the chart will show afterwards what the approximate rate of discharge has been at a particular moment—though the scale of the diagram is far too small for accurate information on this question. But what a quantity meter cannot possibly do is to help an attendant to perform the indispensably necessary and frequently recurring operation of manipulating a control valve so as to send along a pipe a certain specified discharge. He therefore needs an instrument graduated in units of rate of flow whose indications will instantly follow the movements of the valve as he opens or closes it, and he wants to be sure that as soon as the indicator reaches the desired figure then the specified discharge is passing.

If he is given the further duty of maintaining the flow constant, here again he will have nothing further to do than to open or close the valve a little so as to keep the flow indicator steady on its mark. Some such instrument will be all the more necessary if, as so often happens nowadays, an automatic device is left in charge of flow control.

110. Basic Principles of Rate-of-flow Meters. Meters which overcome all the limitations just enumerated are available in great variety: they can be used in very large pipes, each conveying up to 20 tons of water per second, they will meter such unpromising liquids as crude sewage, and they do rapidly respond to variations in the rate of discharge. In order to accomplish these things they almost invariably abandon completely the principle of counting measured volumes, and they use instead an indirect principle—the principle of measuring differential head and deducing from this the rate of flow. There are thus two functionally different components in all such measuring installations—a *primary* element in which the liquid during its passage generates a differential head, and a *secondary* element which measures the differential head. The secondary element may take the form of one of the various differential gauges mentioned in Chapter I, and it may work

in conjunction with the recording, translating, and integrating devices described in Chapter XIII ; it will not be discussed in detail in this chapter, which is concerned mainly with primary devices.

Although the most usual way of creating a differential head is to form in the pipe-line a constriction or throat through which the liquid is obliged to pass with augmented velocity, it is possible to dispense with a throat by choosing as the measuring site a bend in the pipe where a ready-made centrifugal differential head already exists. Alternatively, the difference between the head at the impact orifice and the head at the static orifice of a Pitot tube may very conveniently be employed. There is finally a class of instrument in which the differential head is allowed to alter the position of elements in the primary device, whose own movements thus give a measure of the discharge ; they are known as variable-area meters.

111. Characteristics of Differential-head Meters. The fundamental relationship between differential head and discharge, no matter how the head is generated, is that the discharge varies as the *square root* of the differential head. From this law two difficulties arise, one major and one minor. The greater defect occurs at the lower end of the measuring range, for it is clear that when the measured discharge is, say, one-tenth of the maximum discharge, the observed differential head is only *one-hundredth* of the maximum scale reading—an amount which it is wholly impossible to measure with any degree of reliability. Consequently, rate-of-flow meters are generally much inferior to quantity meters in this respect. At the other end of the scale—or rather beyond the scale—we come to the question of overloads : the question of what is going to happen if the discharge materially exceeds that for which the meter was designed. Manifestly the differential head will increase very rapidly, and may soon cause troubles in the gauge itself which have to be specially guarded against (§ 54). Quantity meters, on the other hand, and especially inferential ones, have a very comfortable overload capacity—the discharge may momentarily be double the normal maximum without harming the meter in any way.

It is much more difficult to compute total flow from the indications of a rate-of-flow meter (Chap. XIII) than it is to

compute average rate of discharge from a quantity meter. Nor is it possible to reverse the flow through a constriction meter : as a rule the indications of such a meter would be meaningless if the liquid passed through in the wrong direction. But quantity meters of suitable type may be adapted to register the *net* flow, adding if the flow passes in one direction and subtracting if in the other.

An advantage common to most types of differential-head meter is that in flowing through them the liquid does not come into contact with any working or moving parts ; this greatly simplifies the question of maintenance. Moreover, the fact that the secondary element may be fixed scores of feet away from the primary element (§ 44) facilitates the installation of the meter.

CONSTRICTION METERS

112. Fundamentals of Constriction Metering. The elements of a rate-of-flow meter in which a constriction forms the primary device are shown diagrammatically in Fig. 75. The constriction is of generalised circular shape, having a clear opening of diameter d ; and because of the principle of continuity of flow, we can say that

$$\frac{\pi}{4}D^2v = \frac{\pi}{4}d^2V,$$

where D = diameter of pipe,
 d = diameter or bore of constriction,
 v = mean velocity in pipe,
 V = mean velocity in constriction.

It is the purpose of the installation to determine the unknown velocity v , and thus to find the discharge.

The changes in pressure and velocity which enable the reading of the secondary element—in this instance a U-tube glass-tube gauge—to serve as a measure of the flow are represented by the conventional energy line and head line or hydraulic gradient. In passing through the constriction the liquid suffers a rapid drop of head h , the pressure thereafter rising somewhat until at some little distance downstream of the meter the hydraulic gradient again becomes nearly horizontal. It is this head drop h which is registered to a suitable

scale on the differential gauge and which is termed the *measuring head*. Meantime the effect of the violent eddying downstream of the constriction has been to dissipate energy and to cause a corresponding droop of the energy line. The resultant overall loss of energy h_v , which is here identical with the overall head drop, is called the *head loss* of the meter.

What we want in practice is the *maximum* measuring head, so that the indicating device of the secondary element may have a good open scale, but we want the minimum *head loss* because it represents a direct waste of energy. To avoid the necessity of calibrating the meter by means of a measuring

tank, moreover, it is quite essential that the constriction should be of a simple, standardised, and easily reproducible form. The forms that have been found most convenient in practice are the Orifice, the Nozzle, and the Venturi Tube. Finally, it is clear from the shape of the hydraulic gradient (Fig. 75) that the position of the positive and negative

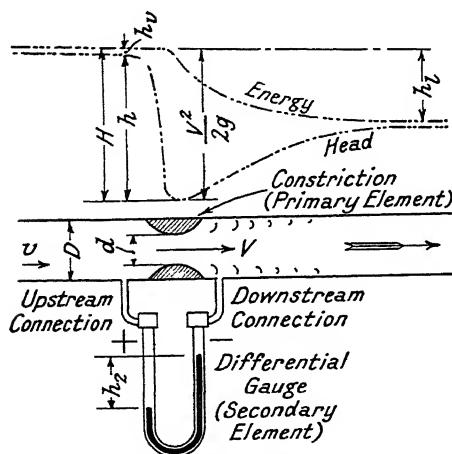


FIG. 75.—Elements of constriction meter.

upstream and downstream pressure connections, will also influence the differential head and must therefore be standardised.

113. General Equations for Constriction Meters.

Let h = differential head of *metered liquid*.

A = area of pipe or inlet section of passage.

a = area of constriction or throat.

β = diameter ratio for circular sections = $\frac{d}{D}$.

m = area ratio = $\frac{a}{A}$ = (for circular sections) $\frac{d^2}{D^2} = \beta^2$.

h_v = velocity head at inlet section = $\frac{v^2}{2g}$.

Applying the Bernoulli equation to the conditions represented in Fig. 75, we can write (referring total energy to the appropriate datum plane)

$$H = h + h_v = \frac{V^2}{2g}, \quad \text{or} \quad h = \frac{V^2}{2g} - \frac{v^2}{2g}.$$

But since $Av = aV$, then $v = mV$, and therefore :

$$V = \sqrt{2gh} \sqrt{\frac{1}{1 - m^2}},$$

and the ideal rate of discharge

$$= q_i = aV = a\sqrt{2gh} \cdot \sqrt{\frac{1}{1 - m^2}}.$$

Now because of friction, contraction of the stream in flowing through the constriction, and other causes, the actual, true, or measured discharge q is different in value from the ideal discharge q_i , and the relationship between them can be expressed in two ways:—

- (i) By the use of an arbitrary or empirical coefficient C_d known as the *coefficient of discharge*, having the value $C_d = \frac{q}{q_i}$, which enables the discharge to be computed from the expression

$$q = C_d a \sqrt{2gh} \sqrt{\frac{1}{1 - m^2}}. \quad (15)$$

- (ii) By the use of an empirical coefficient C known as the *contraction coefficient*, which enables the discharge to be computed from the expression

$$q = Ca\sqrt{2gh}. \quad (16)$$

The relation between the two coefficients is thus

$$C = C_d \sqrt{\frac{1}{1 - m^2}} = C_d C_{va},$$

where C_{va} represents the *velocity of approach factor*, $\sqrt{\frac{1}{1 - m^2}}$.

For a meter of given proportions, this factor C_{va} has a constant value ; it varies only with the area ratio in the manner plotted in Fig. 78.

But the values of the coefficients C_a and C depend upon many variables: the shape and size of the constriction, the velocity, density, and viscosity of the liquid, the position of the pressure tapplings, and minor factors as well; and it is only as a result of long series of researches that the values of the coefficients are known with sufficient exactitude for commercial measuring purposes. Practical convenience alone determines which of the two coefficients should be used; in this chapter the coefficient of discharge C_a will usually be preferred.

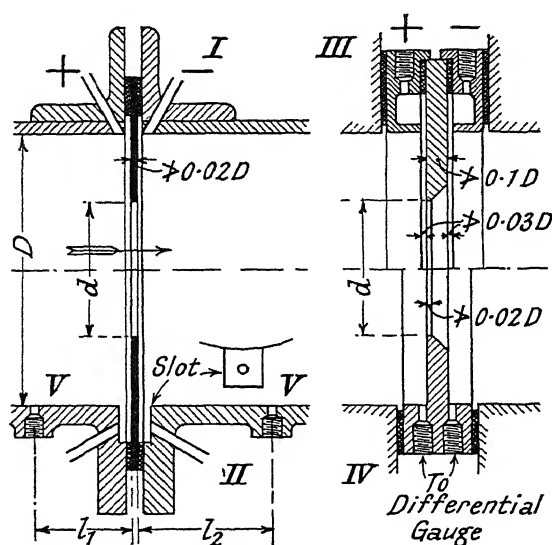


FIG. 76.—Orifice plates.

114. The Orifice Meter. In this, the simplest of all types of constriction meter, the constriction consists of a flat diaphragm having a plain, parallel concentric hole. The orifice plate⁽⁷⁰⁾ is usually clamped between adjacent flanges of the pipe, and may be of such an external diameter that it can be centred by the flange-bolts. Various kinds of construction are shown in Fig. 76. On the left, (I) and (II), the orifice plate is a flat disc of sheet metal having a thickness not greater than $\frac{1}{30}$ of the pipe diameter; on the right, (III) and (IV), the plate is machined from a casting, the finished thickness of

which is not greater than $\frac{1}{10} D$, and it has a narrow parallel or cylindrical section and a bevelled downstream section.

The metal from which the orifice plate is made must be chosen to suit the liquid. Bronze, brass, stainless steel, and monel metal are all likely to be useful. The utmost possible accuracy in machining is essential, particular care being taken that the upstream face of the orifice plate is smooth and flat, and that the upstream circumferential edge of the orifice itself is dead sharp and square—no rounding whatever is permissible. As explained in § 84, this can best be assured by taking a very light finishing facing cut, traversing the tool from the bore outwards.

115. Location of Pressure Tappings. The following are some of the standard locations of the pressure connections :—

Corner taps. The intention here is to measure the upstream and downstream heads at points as nearly as possible in the plane of the orifice plate itself. At (I), Fig. 76, holes are drilled diagonally through the flanges very close to the faces; at (II) the holes communicate with slots cut in the flange faces. Carrier rings are used at (III); the internal diameter of the rings is the same as the pipe diameter, there is a narrow annular slot between the inner lip of the rings and the plate, and thus the mean pressures can effectively be communicated to the liquid in the annular chambers and so through the positive and negative connections to the differential gauge. The orifice plate (IV) has a circumferential collar cast integrally with it, in which the communicating holes are drilled. Because of the steepness of the pressure gradient near the orifice plate the diameter of the holes should be as small as possible consistent with the recommendations of § 43.

Pipe wall taps. Plain holes in the pipe walls are often simpler to arrange than corner taps; the terminology used in defining them⁽⁷¹⁾ depends upon the distances l_1 , l_2 (Fig. 76 (V)) between the pressure openings and the orifice plate.

116. Orifice Coefficients. Apart from minor disturbances it is found that for a given type of pressure tapping the values of the coefficients C_d and C for the orifice meter depend only on (i) the orifice area ratio, and (ii) the nominal Reynolds number which defines the flow, this number itself including

such terms as the orifice diameter and the velocity and viscosity of the liquid.

Experiments⁽⁷²⁾ carried out at the Imperial College, London, give results which are typical of general tendencies, and the basic ones are summarised in Fig. 77, in which the value of the coefficient of discharge C_d is plotted against the orifice area ratio m . The full lines relate to the experiments with *corner taps* (§ 115), while the broken line and the corresponding values of C'_d relate to *pipe-wall taps* (Fig. 76 (V)) in which the distance l_1 is equal to the pipe diameter D , and the total distance $l_1 + l_2$ between the tappings is $1.5 D$ —an arrangement described in

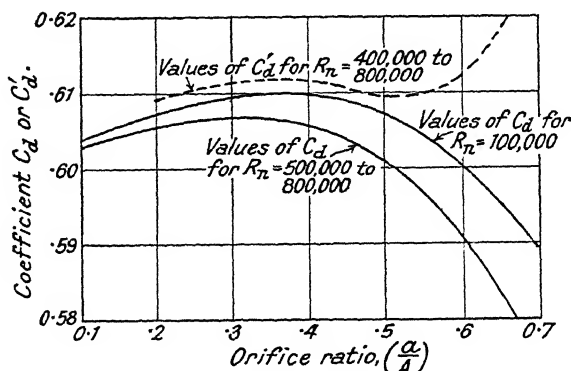


FIG. 77.—Coefficients for orifice meters. (C_d for corner taps. C'_d for pipe-wall taps.)

America as *radius taps*. The Reynolds numbers R_n are based upon the nominal conditions of flow in the *orifice*, viz.

$$R_n = \frac{\sqrt{2gh} \cdot d}{\nu}.$$

In general, it will be seen that for a given value of the area ratio m , the value of the coefficient remains constant so long as the Reynolds number exceeds a certain limit; but when R_n falls below this limit the coefficient C_d gradually rises, the trend being thus identical with that revealed in Fig. 57, § 83.

When it is remembered that the graphs in Fig. 77 do not purport to be other than mean curves drawn between experimental points that may scatter quite appreciably, it is justifi-

able for many practical purposes to condense the information still further, thus :

For *corner taps*, for nominal Reynolds numbers above 100,000, and for area ratios m between 0.1 and 0.5, the mean value of the coefficient of discharge C_d may be taken as 0.605.

For *pipe-wall taps* of the stipulated kind, for nominal Reynolds numbers above 200,000, and for area ratios between 0.2 and 0.5, the coefficient of discharge C'_d may be taken as 0.612.

These values are applicable for *any liquid*; and the values for corner taps may also be accepted with the necessary reserve for the *free-flow orifices* described in § 93 (ii).

To facilitate provisional calculations, which can afterwards if desired be corrected with the help of formula (15), the chart reproduced in Fig. 78 has been prepared. A mean coefficient of discharge of 0.605 has been taken for orifice meters with corner taps, and a coefficient of 0.975 for flow nozzles and Venturi meters.

117. Orifice Meter Calculations.

Example (i): Water at a temperature of 55° F. flows through a pipe 9.0 ins. diameter in which an orifice 4.75 ins. diameter is interposed. Pipe-wall taps are used, and the differential head is measured by a U-tube mercury gauge. What would be the discharge when the deflection of the gauge is 0.262 ft. ?

From formula (5), § 15, the differential head of metered liquid is

$$h = 0.262 \left(\frac{13.59}{1.00} - 1 \right) = 3.30 \text{ ft.}$$

Area of pipe A = 0.441 sq. ft.

Area of orifice a = 0.1229 sq. ft.

Area ratio m = 0.278.

Velocity of approach factor = $\sqrt{\frac{1}{1-m^2}} = 1.042$.

Kinematic viscosity of water at 55° F. = 0.000013 sq. ft./sec.

Nominal Reynolds number

$$= R_n = \frac{\sqrt{64.4 \times 3.30 \times 0.395}}{0.000013} = 444,000.$$

From Fig. 77, the corresponding value of C'_d is 0.611.

Finally, we find from formula (15), § 113,

$$\begin{aligned} q &= 0.611 \times 0.1229 \times 8.03 \times 1.816 \times 1.042 \\ &= 1.14 \text{ cu. ft./sec.} \end{aligned}$$

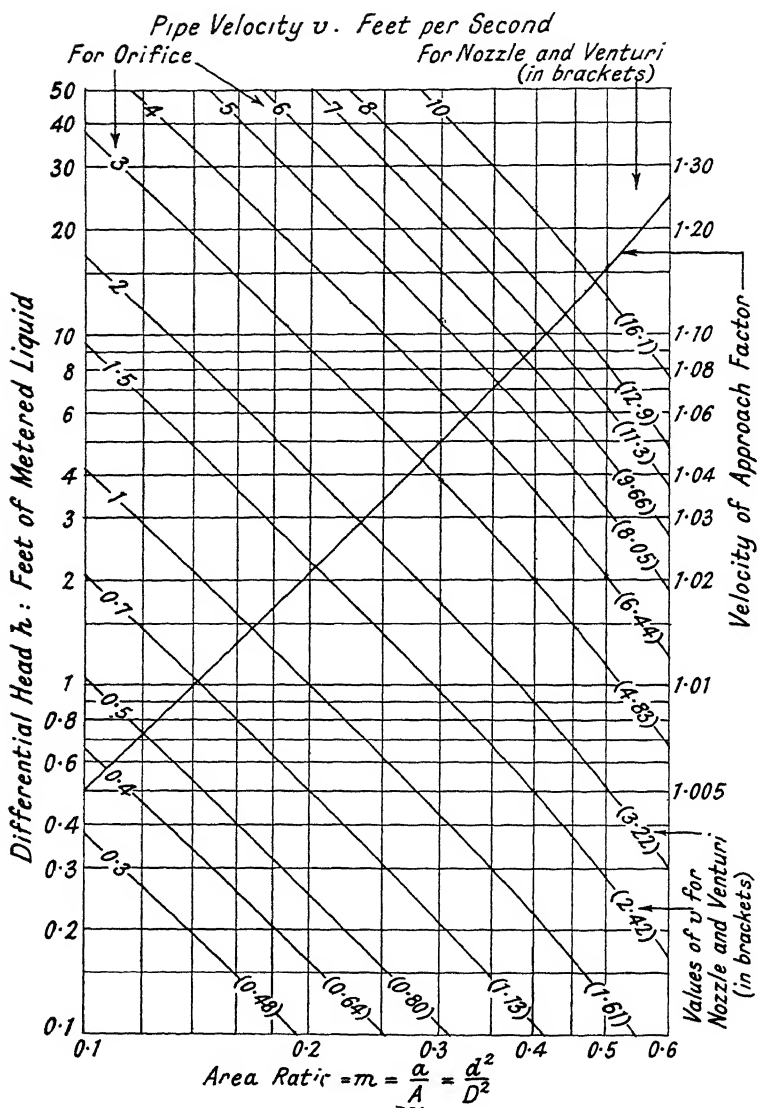


FIG. 78.—Flow chart for constriction meters, based on $C_d = 0.605$ for orifice, and $C_d = 0.975$ for nozzle and Venturi tube.

The flow chart, Fig. 78, could be used to give an approximate solution as follows :—

By noting the intersection of the lines $m = 0.278$ and $h = 3.30$,

$$v = \text{velocity in pipe} = 2.6 \text{ ft./sec.}$$

Therefore $q = Av = 0.441 \times 2.6 = 1.15 \text{ cu. ft./sec.}$

Example (ii): It is required to meter the flow of oil of S.G. 0.88 and Redwood viscosity 96 seconds passing along a pipe of 6 ins. diameter. The maximum discharge is expected to be 500 gals. per min., and the maximum permissible differential head of oil is 15 ft. What diameter of orifice meter would be applicable, and what would be the appropriate flow coefficient?

The values to be inserted in formula (15), § 113, are—

$$\begin{aligned} q &= \frac{500}{374} = 1.336 \text{ cu. ft./sec.}, \\ C_d &= 0.605 \text{ (assumed provisional value),} \\ a &= mA = m \times 0.1963 \text{ sq. ft.}, \\ h &= 15 \text{ ft.} \end{aligned}$$

Solving for m , we find that its value is 0.342, and therefore

$$\text{Orifice diameter} = 0.5 \times \sqrt{0.342} = 0.293 \text{ feet.}$$

By using Fig. 78 a quick solution is reached. The maximum discharge in the 6-in. pipe corresponds to a pipe velocity v of 6.82 ft./sec., and this value, together with the value of $h = 15 \text{ ft.}$, enables the value of m to be read off at once, i.e. area ratio = 0.34.

It now remains to be seen whether the provisional value of $C_d = 0.605$ will be applicable here.

Converting the Redwood viscosity to absolute units, it is seen that kinematic viscosity

$$\begin{aligned} &= \nu = \left(0.00247 \times 96 - \frac{0.65}{96} \right) = 0.23 \text{ sq. cm./sec.} \\ &= 0.23 \times 0.00108 = 0.000249 \text{ sq. ft./sec.} \end{aligned}$$

Nominal Reynolds number

$$= R_n = \frac{\sqrt{64.4 \times 15 \times 0.293}}{0.000249} = 36,500.$$

This value falls appreciably outside the range of Fig. 77, and one could therefore only estimate that the coefficient of discharge C_d would be about 0.62 at maximum flow, and 0.63 or 0.64 at lower flows. Thus the meter could not be depended on unless it were calibrated.

If, however, the liquid were kerosene with a kinematic viscosity of 0.02 sq. cm./sec., then the Reynolds number at maximum flow would be 450,000 and the coefficient of discharge C_d for corner taps would be (from Fig 77) 0.607. This value is quite near enough to 0.605 to justify the use of the flow chart (Fig. 78) in connection with this meter.

118. The Flow-nozzle Meter. In the flow nozzle (Fig. 79) the contraction of the stream takes place wholly within the

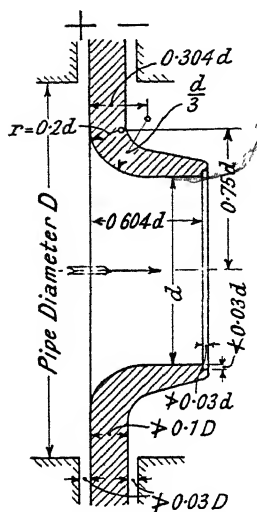


FIG. 79.—Flow nozzle.

constriction, the liquid issuing from it in the form of a parallel jet. It therefore differs from the orifice, which creates a jet materially smaller in diameter than the orifice itself. It is only when large area ratios must be used—say, in excess of 0.4—that the nozzle had advantages over the orifice, but on the other hand the orifice is more easily machined to the specified standard shape. The proportions quoted in Fig. 79 are those recommended by the International Standardising Association (I.S.A.) and by the German *Rules for Flow Measurement with Standard Nozzles and Orifices*; ⁽⁷³⁾ this publication shows how to estimate the value of the constriction coefficient

C when corner taps are used, both with nozzles and orifices. Valuable information about orifices is contained also in the American *Fluid Meters* report. ⁽⁷¹⁾

For approximate purposes the following information will serve:—

So long as the nominal Reynolds number exceeds 200,000, and corner taps are used, the value of the *coefficient of discharge* C_d to be used in formula (15) will vary from

0.987 with an area ratio m of 0.05
to 0.946 with an area ratio of 0.45.

By choosing a provisional mean value of $C_d = 0.975$, the figures enclosed in brackets in the flow chart (Fig. 78) permit this chart also to be used for nozzle meters.

119. Accuracy of Orifice and Nozzle Measurement.

Before assessing the overall possibilities of error in the use of the orifice and the nozzle it is essential to examine the effect of variations in the mode of installation, observing that these effects are nearly always related to the area ratio m .

(i) *Faulty approach conditions.* Anything that prevents the liquid from approaching the constriction axially, in the form of a steady uniform stream, will increase the difficulty of correctly estimating the appropriate value of the coefficient C_d . The minimum length of straight pipe of uniform diameter D that must immediately precede the constriction, in order to avoid this uncertainty, may vary from $5 D$ with small values of m to $20 D$ with large values of m , an average value being $10 D$. The corresponding length of straight uniform pipe downstream of the constriction may be taken as $5 D$. The inlet lengths here specified will be insufficient if at the upstream end there is a tapered enlargement or a partially-closed valve.

(ii) *Roughness of pipe wall.* For area ratios greater than 0.3, the effect of very rough or tuberculated pipe walls may be to increase the value ⁽⁷⁵⁾ of the coefficient C_d .

(iii) *Lack of alignment.* Errors falling under this heading are those caused by mounting the orifice or nozzle eccentrically in the pipe, by using jointing material cut to a smaller diameter than the pipe diameter, and so on.

(iv) *Incorrect estimation of pipe diameter.* If the meter is inserted in a line of rough commercial pipe, it may be difficult to measure accurately the mean diameter D , and thus to define the value of m . This uncertainty, especially with large area ratios, will be reflected in the final estimate of the discharge.⁽⁷⁴⁾

Even when all reasonable care has been taken, then, it is hardly warrantable to expect an overall range of error of much less than ± 2 per cent. when estimating the flow through standard orifices and nozzles. The only certain way of reducing this range is to calibrate the entire flow-metering equipment by the use of a measuring tank.

120. Head Loss in Orifice and Nozzle Meters. The overall loss of energy or the head loss h_l created by an *orifice* meter can be found approximately from the relationship

$$h_l = h(1 - m),$$

where h is the measuring head (Fig. 75).

The corresponding relation for a *flow nozzle* is even more of a rough approximation. It is

$$h_i = h(1 - em),$$

where e is a factor depending on the area ratio as follows :—

Value of area-ratio m .	0.1	0.2	0.3	0.4
Value of factor e .	1.60	1.56	1.51	1.43

Another useful approximation is that for a given pipe, a given discharge, and a given differential head, either an orifice or a nozzle would produce the same head loss.

The typical shape of hydraulic gradient created by a nozzle is presented by the appropriate curve in Fig. 83 ; as the area ratio is here 0.25, the energy loss as computed by the above formula is $0.61h$, which agrees well enough with the actual loss of 59 per cent. of h .

When comparing the head loss in constriction meters with the loss in other types of meter it is convenient to express the loss in terms of the velocity head, as in the following table :—

Type of meter.	Area ratio <i>m</i> .					
	0.1	0.2	0.3	0.4	0.5	
Orifice meter .	240	50	20	9	4	Approximate value of factor <i>K</i> $= \frac{\text{Head loss}}{\frac{v^2}{2g}}$ where <i>v</i> = velocity in pipe. (§ 96 (iv).)
Flow nozzle .	84	17	6	2.3	—	
Normal Venturi tube (§ 123) $h_t = 0.12 h$.	12	3	1.2	0.6	—	
Positive meter .	From about 3 to 40					
Inferential meter .	From about 0.6 to 20					

As pointed out in §§ 112 and 119, the advantages of choosing as small an area ratio as possible are that a comfortably large measuring head will be generated, and that the coefficient of

discharge will suffer relatively little from disturbances in the approach conditions. The above table shows clearly enough what is the price, in terms of energy loss, that must be paid for these advantages. (See also *Example (ii)*, § 123.)

121. The Short Venturi Tube. The energy loss imposed by an orifice or flow nozzle is a result almost wholly of the random eddying motion that occurs downstream, in the zone in which the jet gradually expands to the full pipe diameter. But it is by no means inevitable that the expansion should be accompanied by so large a loss of energy—on the contrary, there exists a familiar and effective hydraulic device which will greatly reduce the loss: this device is a diverging tail-pipe or energy recuperator fitted between the nozzle outlet and the downstream section of the pipe. The addition has virtually no effect on the differential or measuring head; its sole effect is to reduce the head loss.

The combination of a flow nozzle and a conical enlargement is called a short Venturi tube, to distinguish it from the normal Venturi tube which has much longer inlet and outlet sections. A

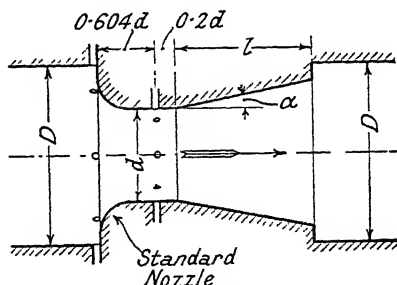


FIG. 80.—Short Venturi tube.

short tube embodying a standard flow nozzle (§ 118) is shown in Fig. 80. The distance between the rings of upstream and downstream pressure connections is identical with the length of the standard nozzle; then follows a parallel throat equal in diameter to the nozzle diameter and of length $0.2d$; finally comes the conical enlargement of length l and of half-angle of taper α . It has been found⁽⁷⁶⁾ that so long as the area ratio of the nozzle is not greater than about 0.5, then its coefficient does not differ by more than 1 per cent. from its normal coefficient when used without the conical enlargement (§ 118).

In designing the conical enlargement the object is to find the half-angle α which, for a given length l , gives the minimum head loss h_l . This angle varies between about 6° and 11° ; its optimum value when m is 0.49 and $l = 0.7D$ is 8° , and the energy loss will then only be about 12 per cent. of h . With

smaller values of m and of l the possibilities of energy recuperation are naturally less promising.

The short Venturi tube has lately advanced rapidly in favour as experimenters have found that it gives nearly the same results as the normal Venturi tube at much less cost.

122. The Normal Venturi Tube. It is only because in this chapter the simplest types of constriction meter have been discussed first that the Venturi meter appears last. In other respects it deserves first place: on account of its honourable history, the well-merited reputation it enjoys, and the unique advantage it possesses of causing the absolute minimum of head loss. On these grounds the Venturi meter is the type

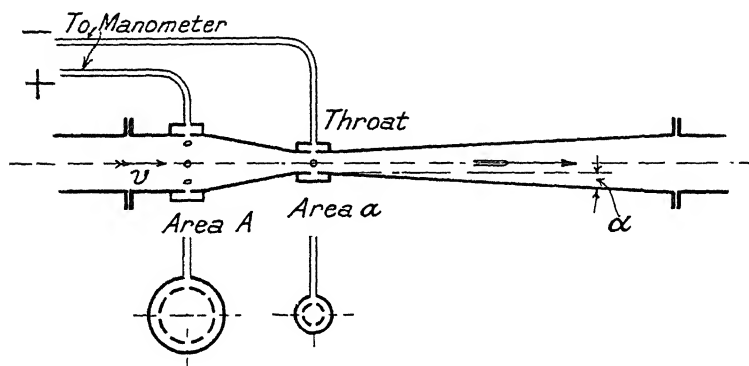


FIG. 81.—Normal Venturi tube.

of constriction meter that is usually, but not always,⁽⁷⁷⁾ preferred for measuring large flows; flows, that is to say, passing in pipes of about 12-in. diameter and over.

The simplest form of meter, shown diagrammatically in Fig. 81, has an upstream converging cone or inlet section having a half-angle of taper of 10° or so, then a short parallel throat, and an outlet or expanding cone having a much smaller taper, the half-angle ranging between 6° and $2\frac{1}{2}^\circ$. Both sets of pressure tapings consist of a circumferential row of holes communicating with a belt from each of which a pipe leads to the differential gauge; the location of the positive tapings is in the parallel section which matches the pipe, and the negative tapings are half-way along the throat. To ensure that the areas A and a are accurately defined, machined brass sleeves

are usually let into the castings here, so eliminating the uncertainty referred to in § 119 (iv). The variations of design in meters made by different firms are found as a rule in the converging inlet; instead of this being truly conical, it may be trumpet-shaped, the angle of flare diminishing as the throat is reached so as to give a better stream-lined form. Alternatively the inlet length may be formed of two reverse curves which give an ogee effect.

123. Coefficients and Head Loss in Venturi Meters.

In the absence of international standards for the design of

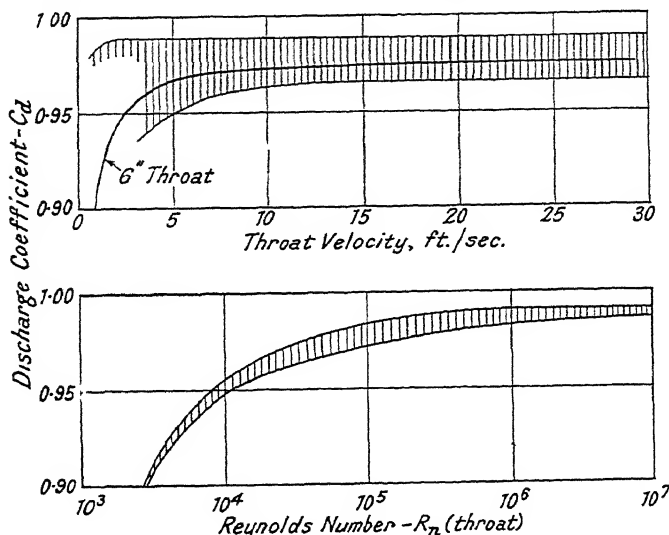


FIG. 82.—Venturi tube coefficients.

Venturi tubes, only approximate indications can be given of the value of the coefficient of discharge C_d to be used in formula (15), § 113. Large meters used for measuring water flows have coefficients of the order of 0.98-0.99, the precise values being determined by the manufacturers; there is usually a tendency for the coefficient to diminish at low rates of discharge or with small meters.⁽⁷⁸⁾ If the coefficients of meters with conical converging sections (Fig. 81) are plotted against throat velocity V , the observed values are likely to fall within the hatched zone in the upper chart of Fig. 82 which relates to pipe diameters from 36 ins. to 2 ins.; the full line shows the

characteristics of a meter having a 6-in. throat. The trend is more clearly shown by plotting values of discharge coefficient C_d against Reynolds number (based on throat conditions), as in the lower chart,⁽⁷⁹⁾ and this has the advantage also of taking into account the properties of the metered liquid. It is probable that a stable coefficient, unaffected by variations over a wide range of throat velocities, is more easily attainable in a meter having an inlet section that is not a simple cone. In the flow chart (Fig. 78) the mean coefficient for provisional Venturi-meter calculations has been taken as 0.975.

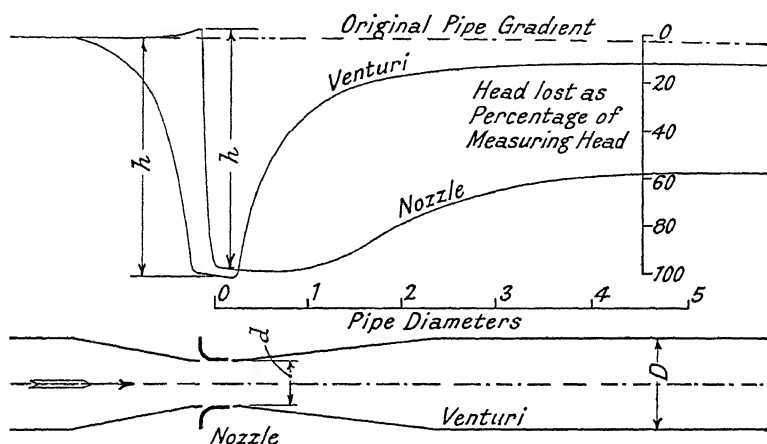


FIG. 83.—Comparative hydraulic gradients produced by nozzle and Venturi tube.

The head loss incurred by the use of a Venturi meter naturally varies with the area ratio m and with the downstream half-angle α ; the value of the loss h_l is normally between 9 and 12 per cent. of the measuring head h . Fig. 83 is instructive in showing on a comparative basis the hydraulic gradients along the axis of a pipe having (i) a flow nozzle, and (ii) a Venturi meter in which the downstream half-angle α is $6\frac{1}{2}^\circ$. The area ratio for both constrictions is 0.25. In neither case is the recovery of head completed before a point about six pipe diameters downstream from the throat.

Example (i): What would be the size of throat and the value of the coefficient of discharge if a Venturi meter were used to measure the oil flow specified in *Example (ii)*, § 117?

From Fig. 78 (figures in brackets) the approximate value of m is found to be 0.217, from which $d = \text{throat diameter} = 0.232$ ft. Also nominal Reynolds number = 29,000, and thus from lower chart (Fig. 82) $C_d = \text{about } 0.965$.

(Note that as the discharge falls off, C_d diminishes appreciably; at 30 per cent of maximum flow its value would only be about 0.94.)

The values so obtained can now be inserted in formula (15), § 113, to establish the true relationship between head and discharge.

Example (ii): A flow of 6.75 million gallons of water per day is passed along a 24-in. main in which a constriction meter generating a measuring head of 10 ft. is installed. The overall cost of pumping the water is one penny per water-horse-power hour. What would be the annual power cost of metering the water if (a) a Venturi meter, (b) an orifice meter, were chosen?

6,750,000 gals. per day = 12.55 cu. ft./sec., and thus $v = \text{pipe velocity} = 4.0$ ft./sec. From Fig. 78 the area ratio m for the Venturi meter is found to be 0.16, and for the orifice meter, 0.25. From § 120 and Fig. 83, the ratio

$$\frac{\text{Head loss}}{\text{Measuring head}}$$

will be about 0.12 for the Venturi meter, and 0.75 for the orifice meter.

The corresponding head losses are 1.2 ft. for the Venturi meter and 7.5 ft. for the orifice meter.

The respective power losses are

$$\frac{1.2 \times 12.55 \times 62.4}{550} = 1.7 \text{ w.h.p.}$$

$$\text{and} \quad \frac{7.5 \times 12.55 \times 62.4}{550} = 10.7 \text{ w.h.p.}$$

The annual costs are

$$\frac{1.7 \times 24 \times 365}{240} = \text{£62 for the Venturi meter,}$$

$$\frac{10.7 \times 24 \times 365}{240} = \text{£390 for the orifice meter.}$$

Although these figures, being based on uniform full discharge, are comparative only, they show conclusively that the relatively high initial cost of installing a Venturi meter is as a rule justified.

124. Other Forms of Venturi Passage. The principle of the Venturi meter is in no way bound up with a passage

of circular cross-section. Especially in very large meters it is sometimes found convenient to make both the inlet and the throat sections of rectangular form, the floor and roof of the passage being flat and thus offering no encouragement either to the deposition of solids or to the accumulation of gases.

An inexpensive method of converting a steel pipe into a Venturi meter is illustrated in Fig. 84 (I); two pieces of steel plate are cut and bent to shape and welded inside the pipe so as to form a throat of nearly rectangular section in which the necessary pressure tapings are drilled.⁽⁸⁰⁾ The inlet section is of course circular. In Fig. 84 (II) the throat is of annular cross-section, and is in fact the passage between the outer body and the inner casing of a needle valve. The makers of this

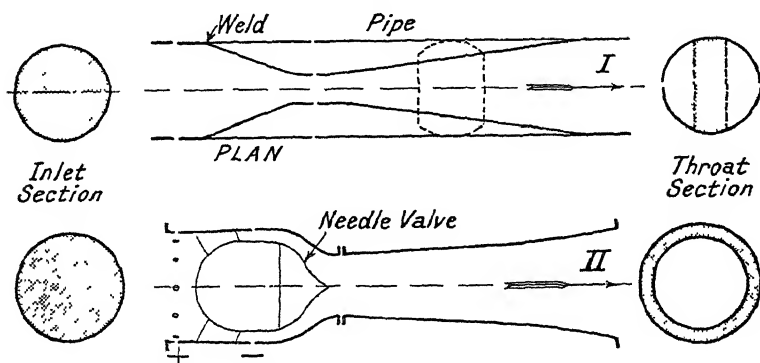


FIG. 84.—Alternative forms of Venturi passage.

patented combination, Messrs. Bopp & Reuther, claim that the meter coefficient is not sensibly altered by movements of the valve, and in other respects, too, the combination of the valve and the meter is a very happy one, economising both in overall length and in overall head loss.

Manifestly all such devices require individual calibration. With this proviso, parts of an existing pipe-line can sometimes be adapted for flow measurement, the most promising section to investigate being one in which the pipe uniformly tapers to a smaller diameter.

125. Means for Increasing the Range of Registration of Constriction Meters. It will now be evident that when set to measure small flows, constriction meters suffer from

another drawback additional to the fundamental one mentioned in § 111; not only is the differential head generated too small to be accurately measured, but the coefficient C_d on which the whole process depends may itself lose its constancy and become variable and increasingly uncertain (Figs. 77 and 82).

(i) *Meters in parallel.* One way of overcoming this disability has already been suggested, for it was shown in § 82 that orifice gauging tanks arranged in parallel have quite a wide measuring range. In precisely the same manner, Venturi meters of different capacities can be arranged in parallel, so ensuring an ample range of discharge without the need to use the unreliable lower part of the meter characteristics. This system was chosen for high-precision measurements of pump discharges in the California Institute of Technology ⁽¹¹⁾ (Chap. I.)

(ii) *Interchangeable orifices.* If the constriction is an orifice the measuring range may be extended, although at the cost of interrupting the measurements, by using two or more orifice plates of different area, the large opening being chosen for large flows and the small opening for lower flows, so maintaining a sufficiently high minimum differential head. Designs are also available by which the change can be made without stopping the flow in the pipe and without breaking any joints.⁽⁸¹⁾

(iii) By abandoning the circular opening it becomes possible to have an orifice of *infinitely-variable area*. The complete apparatus then has the form of a precision-built fullway or sluice-valve of special shape in which the valve opening can accurately be read off from an external graduated scale; and this information, together with the differential head, permits the discharge to be computed.

Such appliances require careful calibration, and as they must be adjusted by hand they cannot be used with automatic recorders or integrators.

126. Installation of Constriction Meters. The following notes are additional to those already recorded in connection with the accuracy of orifice meters (§ 119). Obviously care must be taken when installing any meter to avoid the faults there enumerated. The Venturi meter is less sensitive to flow disturbances than other constriction meters are,⁽⁸²⁾ but

that is no reason for handicapping it by tolerating awkward upstream conditions. If it is impossible to arrange the desirable straight length of pipe, ten diameters long, between the last bend, tee, etc., and the entrance to the meter, then *straightening vanes* or honeycombs may often be effective in suppressing eddies and re-imposing parallel flow on the liquid. They are set in the straight pipe, and may consist either of sheet-metal vanes fixed parallel with the pipe axis, or of a bundle of short lengths of thin brass tube filling the pipe.

An important point is to try to choose such a position for the meter that even at maximum discharge the minimum pressure will never fall below atmospheric—and it is to be remembered that at the negative tapping of a Venturi meter the pressure is substantially below the average pressure in the pipe-line (Fig. 83). If this condition cannot be observed, and as a consequence air finds its way into the connecting pipes leading to the differential gauge, then a tiresome vista of troubles may open up (§ 45). Moreover, with volatile liquids there is a greatly increased tendency to vaporisation when the head is low. In general, then, the meter should be placed in the lowest available position in the pipe-line, and special precautions are required when hot water or volatile liquids are being metered. It is exceptionally difficult to arrange a satisfactory constriction meter in the suction pipe of a pump.

Example : An orifice meter having an area ratio of 0.35 is interposed in a 4-in. pipe for the purpose of metering a maximum flow of 130,000 lbs. per hour of water at a temperature of 180° F. What should be the minimum permissible absolute pressure at the upstream tapping ?

Vapour pressure of water at 180° F. = 7.49 lbs./sq. in.

Specific gravity ,, ,, = about 0.97.

$$130,000 \text{ lbs./hr.} = \frac{130,000}{3600 \times 62.4 \times 0.97} = 0.60 \text{ cu. ft./sec.}$$

A = pipe area = 0.0875 sq. ft.

v = pipe velocity = 6.87 ft./sec.

h = measuring head = 14.5 ft., from Fig. 78.

p = differential pressure = 6.1 lbs./sq. in.

Now the minimum absolute pressure at the downstream tapping is the vapour pressure of the water = 7.49 lbs./sq. in. Therefore the minimum pressure at the upstream tapping is $7.49 + 6.1 = 13.6$ lbs./sq. in. With an atmospheric

pressure of 14.7 lbs./sq. in., a vacuum of 1.1 lbs./sq. in. at the upstream tapping would thus be theoretically allowable, but to attempt to realise such conditions would be most inadvisable, for the water at the downstream tapping would be on the point of boiling. To avoid trouble from this cause there should certainly be a few feet of positive head at the upstream tapping.

Apart from atmospheric air that might enter the meter, residual air may have to be vented from the upstream side of an orifice plate (Fig. 76), for otherwise when liquid flow begins there is no escape for the air trapped above the level of the top of the opening. A vent-cock may thus have to be provided here; and if the liquid carries solids in suspension a blow-off cock at the bottom of the pipe may prevent accumulations of solids that would certainly affect the meter coefficient.

127. Measurement of Pulsating Flows. Constriction meters are basically unfitted for the gauging of rapidly fluctuating discharges. The chief reason is that there is no way of damping the oscillations of the differential gauge so that its mean reading will truly represent the mean flow; it was shown in § 67 that the damped reading of the differential gauge used with any square-law primary element always tends to over-estimate the discharge. If, therefore, it is desired to meter the discharge from a reciprocating pump or the supply to reciprocating machines, and the air vessel normally fitted is not capacious enough to smooth out the fluctuations in pipe velocity, then an auxiliary air vessel must be interposed in the pipe-line.

When measuring rapidly accelerating or rapidly retarded flows, the Venturi meter is subject to an error that rarely has any practical importance; it results from the inertia head, generated in the liquid column between the positive and negative tappings, which will slightly falsify the differential head reading.

OTHER TYPES OF DIFFERENTIAL-HEAD METER

128. Centrifugal-head Meters. Whenever liquid flows round a bend in a pipe, as in Fig. 85, a differential centrifugal head is generated between the outer and the inner wall of the bend, and thus if tappings are made at these points the observed

head h may sometimes be used as a measure of the discharge.⁽⁸³⁾ The head-discharge relationship is of the same form as it is for a constriction meter, viz.

$$q = C_d \sqrt{2gh} \cdot (J),$$

where C_d is an experimental coefficient of discharge and J is a factor depending only on the size and proportions of the passage.⁽⁸⁴⁾

If R = radius of curvature of bend, Fig. 85,
 c = one-half of radial depth of cross-section,
 b = axial width of cross-section,

then for a passage of rectangular cross-section,

$$J = \frac{R^2 - c^2}{2\sqrt{Rc}} \cdot 2.303b[\log_{10}(R + c) - \log_{10}(R - c)],$$

and C_d = about 1.00.

For a bend in a circular pipe of radius c ,

$$J = \frac{R^2 - c^2}{\sqrt{Rc}} \cdot \pi[R - \sqrt{R^2 - c^2}],$$

and C_d has the approximate provisional values, subject to an error of perhaps ± 3 per cent., given in the following table:—

It is here assumed that the pressure tapplings are drilled in a plane passing through the centre of curvature of the bend, making an angle of 45° with the inlet and outlet flanges.

Curvature Ratio $\frac{R}{c}$	2	2.5	3	3.5	4	4.5	5	5.5	6
$\frac{h}{\frac{v^2}{2g}}$	3.09	2.07	1.59	1.29	1.10	0.96	0.85	0.76	0.70
C_d	1.25	1.12	1.09	1.07	1.05	1.04	1.03	1.02	1.02

The values of $\frac{h}{\frac{v^2}{2g}}$ listed in the table are rather more convenient than the original flow formula; they give the *ideal* relationship between the centrifugal head and the nominal velocity head in the pipe—a relationship that depends on the curvature

ratio only and not on the size of the bend. It is interesting to observe that in a bend with a curvature ratio of 4 the differential head generated is much the same as it would be, under equivalent conditions, in a Pitot tube with pipe-wall static opening used in a straight pipe.

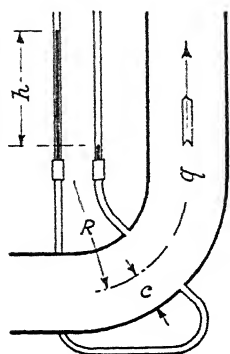


FIG. 85.—Centrifugal-head meter.

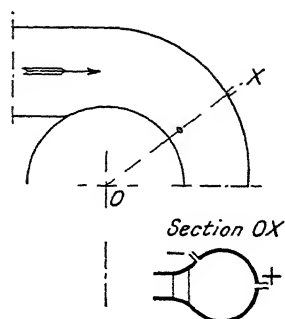


FIG. 86.—Flow measurement in turbine casing.

Example: A bend in a circular pipe 10 ins. diameter has a radius of 18 ins., and the measured differential centrifugal head is 0.38 ft. What would be the approximate discharge in the pipe?

From the table, the value of $\frac{h}{\frac{v^2}{2g}}$ corresponding to a value of $\frac{R}{c}$ of 3.6 is about 1.25, and consequently $\frac{v^2}{2g} = \frac{0.38}{1.25}$, from which v (ideal) = 4.45 ft./sec. Also $C_d = 1.07$.

Therefore $q = 1.07 \times 4.45 \times 0.545$
 $= 2.6$ cu. ft./sec.

The bend meter has the unique advantage that it permits rough comparative measurements to be made without in any way interfering with an existing pipe system. Possibly when further experimental results are made available the value of C_d can be more precisely defined; in the meantime its value in a particular installation can always be found by calibration. It should be added that the differential head generated does not depend materially on the angle of deviation of the bend—even if this angle is only 45° , instead of 90° as it is in the diagram (Fig. 85), the pressure difference persists.

The principle of centrifugal-head flow measurement has also been applied to low-head Francis turbine casings.⁽⁸⁵⁾ Selecting a plane OX (Fig. 86), not too far from the inlet to the scroll-casing, the positive tapping is made on the horizontal diameter, and the negative tapping is drilled just clear of the stay-vanes. The continual diversion of water through the vanes into the runner makes any analytical treatment of the head-discharge relationship impossible, but calibration shows that this relationship is little affected by changes of speed, load, or gate opening.

129. The Pitot Tube. The elements of flow measurement in pipes by the use of the Pitot tube have already been discussed in § 64, Fig. 41 (II). Some of the questions involved in

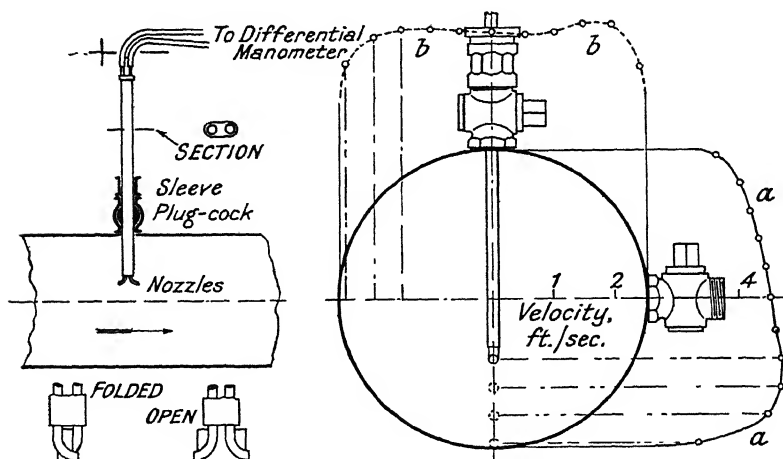


FIG. 87.—Pitot tube installed in pipe.

the practical application of these principles are: (i) The design of the tube itself which will permit the instrument to be easily inserted into the pressure pipe; (ii) the method of locating the impact orifice both as regards position and as regards direction; (iii) the system to be followed in converting readings of *velocity*—which is what the Pitot tube measures—into readings of *discharge*.

One of the best-known commercial instruments⁽⁸⁶⁾ is the Pitometer, which is of the type having an impact orifice and a trailing orifice (Fig. 41 (III)). The two metal tubes leading

to the orifices are enclosed in a sheath passing through a sleeve which can be screwed on to a special plug-cock (Fig. 87); and the orifices or nozzles can be folded together before insertion in the pipe so that the Pitometer will pass through the circular opening in the plug of the cock. When the nozzles are in position they can be opened out, by turning the tubes which connect them to the differential gauge, into the working position. The combination of the sleeve and the cock serves as a "lock" which enables the Pitometer to be inserted into and withdrawn from the pipe without in any way disturbing the flow; it is even possible to drill the hole through the pipe wall and screw the cock into it while the pipe remains under pressure.

An incidental advantage of this construction is that the sheath may be turned through 180° so that the impact orifice becomes the trailing orifice, and *vice versa*; if this reversal has no effect on the observed differential head, it affords fairly convincing evidence that the orifices have not been damaged or choked. To make sure that the nozzles are pointing truly up and downstream, a straight-edge may be laid along the side of the sheath and sighted with respect to the pipe wall. To establish the position of the orifices along the pipe diameter, longitudinal graduations may be engraved on the sheath, and in large instruments a device such as a winch or a feed-screw can be added for traversing the orifices across the pipe and holding them in the desired position.

Whatever other forms of Pitot tube are chosen, similar provision must be made for locating the orifice or orifices, and the mechanical rigidity of the whole outfit must be watched to avoid danger of vibration. If the system of a movable impact opening and pipe-wall static opening is preferred (Fig. 41 (II)), it is desirable to have two or more static tappings equally spaced round the circumference of the pipe, to enable a mean value of the static head to be taken. When using the combined type of tube (Fig. 41 (IV)) the design of the pipe-wall opening through which the tube is inserted may be a little awkward, and special care is required in indicating the angular position of the stem, as a small error will falsify the recorded position of the impact orifice.

130. Single-point Pitot Tube Observations. If the gauging station—the cross-section of the pipe at which discharge

observations are to be made—is at the downstream end of a long, straight, uniform length of pipe where a normal regime of flow exists, then a reasonably close correlation will hold good between the observed velocity at the pipe axis and the rate of flow in the pipe. It therefore suffices to instal the Pitot tube with the impact orifice exactly in the pipe axis, and to make a single velocity observation there. If it is possible to calibrate the tube when in this position by collecting the water in a measuring tank for various rates of flow, a curve can be plotted directly between differential head and discharge, and within narrow limits this curve will hold good for all subsequent measurements. In the majority of cases where such calibration is impracticable, it is necessary to know, in addition to the measured velocity at the pipe axis, (i) the cross-sectional area of the pipe, and (ii) the value of the *pipe factor*. Now the *effective* pipe cross-section must not too hastily be written down; the diameter should accurately be measured at several angular positions in order to determine the mean diameter, and then from the gross area thus calculated an allowance must be deducted for the area of the Pitot tube itself. Just what this allowance should be is a little doubtful. With trailing or Pitometer types of orifices (Figs. 41 (III) and 87) the whole of the projected area of the rod or sheath can reasonably be deducted, while with combined impact and static orifices (Fig. 41 (IV)), the cross-section of the cylindrical sleeve only need be considered.

131. Single-point Calculations. The pipe factor is the ratio between the mean velocity in the pipe, v , and the measured velocity v_m at the centre line, viz. it is the ratio $\frac{v}{v_m}$. Its value depends on the pipe size, on the roughness of the walls, and on the general flow characteristics at the gauging section; consequently as it is not possible to estimate with sufficient accuracy what the value for a given pipe will be it must be experimentally determined. Usually the only way of doing this (apart from direct calibration as already suggested) is to gauge the mean velocity by the integration or traversing method described in the following section (§ 132), and it will then be found that the pipe factor will range in value between 0.75 and 0.90. For a given gauging section the pipe factor is virtually constant, that

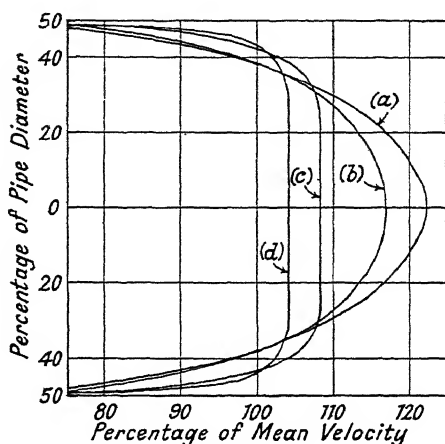
is, it is independent of the rate of discharge, although there is a tendency for the value to rise slightly as the discharge falls off. Typical velocity-distribution curves in pipes are reproduced on a comparative basis in Fig. 88; such curves, it may be noted, are liable to change in shape slightly as the pipe walls become incrustated in the course of years.

When finally the values of the measured velocity v_m at the pipe axis, the effective pipe area A , and the pipe factor $\frac{v}{v_m}$ are available, the required rate of discharge q will be represented by

$$q = Av_m \cdot \frac{v}{v_m}.$$

FIG. 88.—Velocity-distribution curves.

- (a) 12-in. pipe.
- (b) 63-in. welded pipe.
- (c) 80-in. pipe, near inlet bellmouth.
- (d) 16-in. throat of Venturi meter.



The question of the value to be assigned to the Pitot tube coefficient C , in order to evaluate the velocity v_m from the observed differential head h by the use of the formula

$$v_m = C\sqrt{2gh},$$

has already been discussed (§§ 65, 67); but it may here be repeated that for turbulent flow C has an average effective value of 0.98 or 0.976, except for Pitot tubes with trailing orifices, when the value varies with the differential head as shown in the typical calibration curve, Fig. 89.

Example: In order to gauge the flow in a 36-in. pipe a Pitot tube is set with its impact orifice at the pipe axis, and static openings are drilled in the pipe wall. The deflection of the

differential gauge is 0.73 ft., and the indicating liquid in the U-tube is carbon tetrachloride of S.G. 1.59. The pipe factor is known to be 0.86. What would be the discharge? The differential head of water is

$$0.73 \left(\frac{1.59}{1.00} - 1 \right) \text{ (from § 15) } \text{ or } h = 0.43 \text{ ft.}$$

Taking a Pitot tube coefficient of 0.98,

$$v_m = \text{velocity at pipe axis} = 0.98 \sqrt{64.4 \times 0.43} \\ = 5.17 \text{ ft./sec.,}$$

from which

$$q = 7.07 \times 5.17 \times 0.86 = 31.3 \text{ cu. ft./sec.}$$

(No deduction has here been made from the gross area of the pipe, viz. 7.07 sq. ft.)

132. Traversing or Integration Method. This method is based on the fundamental principle that since the actual

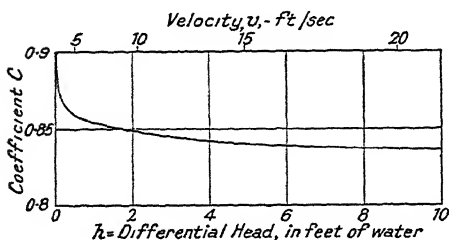


FIG. 89.—Pitometer rating curve

velocity in the pipe varies from point to point in the cross-section, the only sound way of determining the total discharge is to divide up the cross-section into a number of small elements, measure the velocity at the

middle of each element, multiply each velocity by the area with which it is associated, and then total up the products so that

$$q = \Sigma (a_1 v_1 + a_2 v_2, \text{ etc.}).$$

Because of the mechanical difficulty of bringing the Pitot tube orifice in turn to a number of points uniformly distributed over the pipe area, a compromise is usually found adequate: the selected points are chosen along two diameters of the pipe only, and the areas a_1 , a_2 , etc., are all equal. In Fig. 87 the Pitot tube, in this case a Pitometer, is shown being traversed along a vertical diameter; after the differential head at, say, ten or twelve points ranging from one side of the pipe to the other has been observed, the Pitometer is quickly removed and inserted through the horizontal opening, where a similar set of readings is taken.

133. Traversing Method Calculations. The computation of the discharge then proceeds thus: By the use of the Pitot tube calibration curve (Fig. 89), or its equivalent, a table is drawn up giving the velocity at each measuring point, and then, on a scale drawing of the pipe cross-section showing the position of the points, offsets are laid off to represent the velocity; the resulting smooth curves *aa*, *bb* (Fig. 87), form the velocity distribution curves for the vertical and horizontal diameters respectively.

The next step is to divide the pipe cross-section into a number of rings of equal area—10 is a suitable number, though in Fig. 90, for the sake of clearness, 6 only are shown—and to

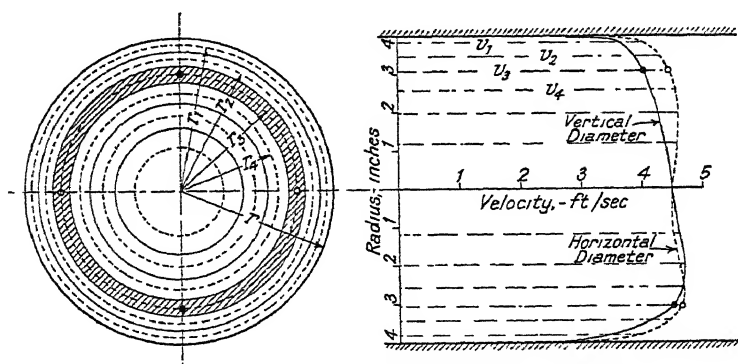


FIG. 90.—Computing discharge from Pitot tube traverse.

sub-divide each ring into two equal areas by the broken lines seen in the diagram. Actually the radii of these broken circles, which are really all that are wanted, can be directly calculated thus:

$$r_1 = r \sqrt{\frac{2n-1}{2n}}; \quad r_2 = r \sqrt{\frac{2n-3}{2n}}, \text{ etc.,}$$

where r is the mean pipe radius and n is the number of rings. From the velocity distribution curves that have been transferred from Fig. 87 to Fig. 90, the velocities v_1 , v_2 , etc., at each of the radii r_1 , r_2 , etc., can be scaled off, resulting in 4 velocity values for each ring (e.g. the ring distinguished by hatching in Fig. 90), or $4n$ values for the whole pipe area. Finally the arithmetical mean of these $4n$ velocities gives the mean pipe

velocity v which, multiplied by the effective pipe area A (§ 130), yields the desired value of the discharge q .

The unsymmetrical shape of the velocity distribution curves, noticeable also in Fig. 93, serves as a reminder that the regular curves reproduced in Fig. 88 can only be realised at the downstream end of a very long straight pipe.

134. Comments on Pitot Tube Measurements. Very varied views are expressed by engineers concerning the reliability of discharge measurements made by Pitot tubes. In spite of discouragements, their supporters persevere in the use of these instruments because they have the incontestable advantages of being able to measure water flow without the need for any permanent alteration to the pipe-line—not a joint need be broken—and without imposing any head loss whatever. Some points *pro* and *con* that may require consideration are—

(i) For low pipe velocities below perhaps 2 ft./sec. the differential head generated is too small for reliable measurement, and, moreover, in this range the coefficient is liable to change rapidly. For a given velocity the Pitot tube with trailing orifice gives a greater differential head than other types, and a still bigger head is possible with special types of orifices using the principle of the Venturi tube.⁽⁸⁷⁾

(ii) Only Pitot tubes adapted for single-point measurement (§ 130) can strictly be regarded as rate-of-flow *meters*, for only they will allow the discharge to be directly read off from the differential gauge or from indicators worked by the gauge. The traversing method, indeed, ought more properly to be classed among the special methods discussed in the following chapter.

(iii) Especially in large-diameter pipes carrying a uniform discharge, the impact pressure registered at a given point is by no means steady: it is subject to oscillations and surges far more violent than those which disturb pipe-wall piezometers (§ 47), the complete cycle of pressure changes occupying perhaps a minute or more. Consequently the only hope of estimating the true mean velocity at the point is to measure the differential head at that point several times in succession, and to insert, as the value of \sqrt{h} in the formula $v = C\sqrt{2gh}$, the mean of the square roots of these differential heads. In the traverse

method it is frequently assumed that the individual errors involved in taking at each point one observation only, instead of a number, will mutually annul one another.

(iv) The length of time required by the traverse method is a serious handicap because of the difficulty of holding the discharge steady during this period of half an hour or more. In an attempt to reduce this handicap the "Photoflow" system has been introduced, in which twenty or more impact orifices and six static orifices are simultaneously in operation, the corresponding piezometric heads being photographically recorded on a single film.⁽⁸⁸⁾

(v) Considerably disturbed flows, such as occur a short distance downstream from bends, branches, and the like, can be measured with fair accuracy by the traverse method. The measurement recorded in Figs. 87 and 90 was made only 8 diameters from a bend and a tee in series, and yet the result agreed within 0.5 per cent. with an absolute measurement. When the only gauging site available involves velocities which are known to be seriously out of parallelism with the pipe axis, there is a chance that the Pitot sphere⁽⁸⁹⁾ (§ 69) might advantageously be tried.

(vi) Pitot tube measurements naturally should not be attempted when the water contains floating or suspended material that would block or damage the orifices, wrap themselves round the rod, or carry away the rod bodily.

SOME OTHER TYPES OF RATE-OF-FLOW METER

135. Variable-area Meters. In these instruments it is the differential head which remains nearly constant and the area for flow which varies as the discharge alters. The example illustrated in Fig. 91 has a casing shaped like that of a globe stop-valve, but in place of the valve seating it has a conical passage which is wholly or partially blocked by a disc at the lower end of a weighted vertical stem. In the no-flow position the disc sinks until it completely fills the conical passage; as flow begins the disc is compelled to rise and so make room for the liquid to pass, and thus the position of the disc serves as a measure of the rate of flow. The simple instrument shown in the diagram has an indicating rod, directly connected to

the weighted stem, which works inside a glass tube and against a scale graduated in units of discharge. These graduations must be arrived at by direct calibration.

Another well-known form is the Deacon waste-water meter, in which the movements of the disc are transmitted by a thin wire to a pen which traces on a clock-driven chart a graph between time and rate of flow. In an American instrument ⁽⁹⁰⁾ the conical tube itself is transparent, the liquid passes directly upwards through it without the need for a casing, and the position of the disc is read off against graduations on the

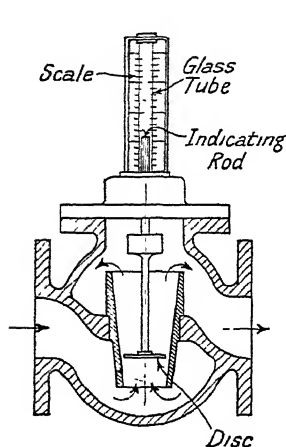


FIG. 91.—Variable-area meter.

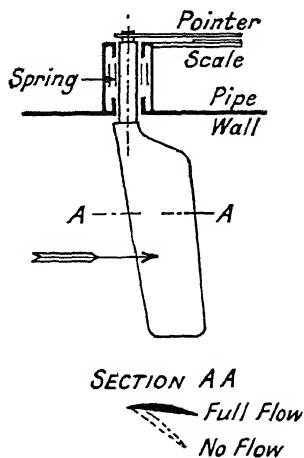


FIG. 92.—Aerofoil flow-indicator.

transparent tube. As the disc is specially shaped, with spiral slots around its periphery, it is caused to spin round continually as the liquid flows past it, and so to maintain itself on a truly vertical axis.

A variant of this arrangement embodies a hollow steel sphere which serves as the disc or plug; its position in the vertical metallic conical tube, and therefore the rate of flow, is indicated by a pointer coupled to a permanent magnet whose poles embrace the tube and follow the movements of the sphere within it.⁽⁹¹⁾ (The principle of the magnetic coupling is illustrated also in Fig. 133.)

Variable-area meters are rarely designed for large flows, they are likely to impose a head loss amounting to many

times the velocity head in the pipe-line, and they score by reason of simplicity rather than of accuracy. But they can be adapted for the measurement of very viscous liquids—liquids such as a Venturi meter would hesitate to accept.

136. Impact Meters. These depend on the dynamic thrust exerted by the liquid on a movable surface inside the pipe; the thrust is resisted by a coiled spring or other elastic element, and consequently as the flow increases the corresponding deflection of the impact surface may be transmitted to an external pointer graduated in units of discharge. In the Seewer Blade Aerofoil Recorder ⁽⁹²⁾ the impact surface is of aerofoil shape (Fig. 92).

In such meters the powerful operating and controlling forces give them a distinct advantage, and they have been used with success in the inlet pipes of turbines. As the calibration will depend on the local velocity distribution in the pipe, impact meters are intended to give a general indication of the flow rather than a precise measurement of it.

CHAPTER IX

MEASUREMENT OF DISCHARGE IN CLOSED PIPES AND CONDUITS

(iii) SPECIAL METHODS

	§ No.		§ No.
Need for special methods	137	Allen method (practice)	145
Current meter measurements		Gibson inertia-pressure method	146
— In circular pipes	138	— Theory	147
— Computations	139	— Practice	148, 149
— Multiple meters	140-142	Calibrated turbine control gear	150
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137. The Need for Special Measuring Methods. It is now necessary to explain why it is that for certain conditions none of the measuring appliances described in the previous chapters are suitable. Such conditions often arise in low-head turbine installations, when each unit may require upwards of 100 tons of water per second flowing through passages the size of a London Tube station; and it is essential that this very great quantity should be measured without any loss of head at all. Yet a heavy responsibility rests on the officials who conduct the tests, for the acceptance or rejection of costly installations, the receipt of a bonus or the forfeit of a penalty, may depend upon the results. It is usually most desirable, too, that the tests should be carried through speedily, because of the operational difficulties in keeping the head and the load steady for any prolonged period.

The general atmosphere in which these discharge measurements are planned and conducted is thus entirely different from that surrounding the working of an ordinary quantity or rate-of-flow meter. The whole aim of the meter is to give clear information which can be read straight away from scales or dials by an unskilled observer. But the methods now to be described require trained crews to carry them out, weeks of

preliminary work in installing the measuring gear may be called for, and the computation and interpretation of the results may take days of labour and very considerable experience and judgment.

If it can by any possibility be arranged, the tests are used for simultaneously calibrating some other part of the turbine equipment which can afterwards itself serve as a meter, e.g. the spiral-casing centrifugal-head meter (§ 128), or the calibrated needle or gate regulator (§ 150).

CURRENT METER METHODS

138. Discharge Measurements in Circular Pipes. By substituting for the Pitot tube orifice a small-diameter propeller type current meter (§ 71 (ii)), an alternative way of conducting the technique described in §§ 129-133 becomes available; it has been successfully employed in pipes as small as 2 ft. diameter, and in very large pipes such as the 20-ft. diameter intakes at the Shannon (Eire) Power Station.

(i) *Single-point system.* Here the current meter is permanently mounted on the pipe centre line, the electrical signalling wires being conducted through the pipe wall. From a knowledge of the pipe factor, the pipe area, the rating characteristic of the meter, and the speed of the meter, the rate of flow can be determined. It will be noticed that the lay-out has some similarity to the helical total-flow meter described in § 103. As limited experience only is available for designing such installations, it would be advisable to inquire very thoroughly into the suitability for continuous running of an instrument normally intended for intermittent service.

(ii) *Traversing method.* The meter is now mounted on the end of a rectangular or a streamlined bar (Fig. 93) in such a way that it can be brought successively to a number of points on each of two pipe diameters at right angles without interrupting the flow.⁽⁹³⁾ Comparing this diagram with Fig. 87, the bar corresponds to the Pitot-tube sheath or rod, and the cover and valve correspond to the sleeve and plug-cock. Being intended for larger pipes than are there shown, the whole equipment is now more heavily built; saddle-castings are required for the valves, and another item is the cover-plate

which follows behind the meter when this is inserted in the pipe and so fills the slot in the pipe wall through which the meter passes. To eliminate the danger of the meter vibrating or being forced out of position, the supporting bar may take a bearing on a fixed transverse guide-bar which serves as a rail. In any event the supporting bar must be grooved or hollowed in such a way that it can accommodate the conductors which transmit the electrical signals from the meter to the external indicating apparatus (§ 72).

139. Discharge Computations. Although the method of calculating the discharge may follow that outlined in § 133,

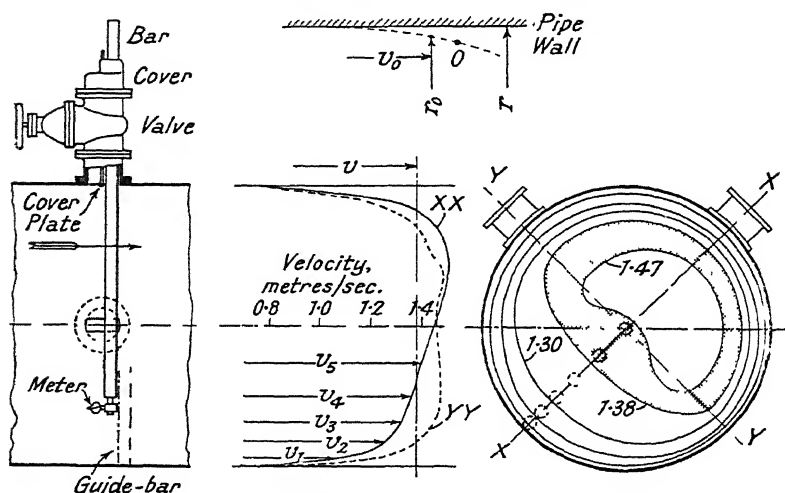


FIG. 93.—Pipe-flow measurement by current meter.

a slightly different system⁽⁹⁴⁾ is shown in Fig. 93; after first setting off the observed velocities v_1, v_2, v_3 , etc., and drawing the two velocity distribution curves XX and YY , lines representing various arbitrary transverse velocity planes are added, whose intersection with the velocity curves permits groups of four points each of equal velocity, e.g. v , to be chosen. By transferring these points to the pipe cross-section, and joining each group by a fair curve, lines of *equal velocity* will result, corresponding in Fig. 93 to velocities of 1.47, 1.38, 1.30, etc., metres per second. The area between each adjacent pair of curves, e.g. the hatched area in the diagram, is now mea-

sured with a planimeter ; and if this area is multiplied by the average velocity, i.e. the mean of the two bounding velocities, or $\frac{1.47 + 1.38}{2}$, then the product will represent the discharge

flowing through that element of the pipe section. Treating all the other areas similarly and summing the products ultimately yields the required discharge through the pipe.

Unlike that of the Pitot tube orifice, the area swept out by the propeller of the current meter cannot be regarded as a geometrical point in relation to the total pipe area, and even though the propeller diameter is as small as 6 cm. it still remains impracticable to explore accurately the very steep velocity gradient near the pipe wall. If the velocity distribution is symmetrical the extrapolation between the point *O* where the last velocity measurement was made (Fig. 93), and the pipe wall itself, may be assisted by the use of the equation

$$v_0 = v_m \left[1 - \left(\frac{r_0}{r} \right)^n \right]^{\frac{1}{n}},$$

where *r* is the radius of the pipe,

*v*₀ is the calculated velocity at radius *r*₀,

*v*_{*m*} is the velocity at the pipe axis,

n is an exponent having a value between 1 and 4. Its precise value can be found from the known radius and velocity at the point *O*.

140. Use of Multiple Current Meters. A technique has been developed, chiefly on the Continent of Europe, of using a number of current meters all running simultaneously for gauging the flow through the intake structures of low-head turbines.⁽⁹⁵⁾ The time required for making a discharge measurement can thus be greatly reduced, and as the current meter signals are invariably recorded on a tape or band chronograph (§ 72), the calculation and analysis of the results is also facilitated. It is often convenient to choose as the measuring section the vertical plane immediately upstream of the grooves designed to receive the emergency gates or stop-logs (Fig. 94) ; a special frame is built, having rollers and hoisting-gear, which can slide up and down in these grooves, its essential component being a horizontal streamlined bar to which the current meters are clamped. Because of the inability of propeller meters to

measure cosine velocity components accurately (§ 75), some sort of temporary roof or partition may have to be improvised, as indicated in the diagram, for diverting the flow into what is near enough to a horizontal plane.

When the equipment has been thoroughly checked and the load and head on the turbine have been adjusted as required, a set of observations is automatically recorded with the frame in its highest position; then the frame is quickly lowered to the next position, and so on, until at the end of only half an

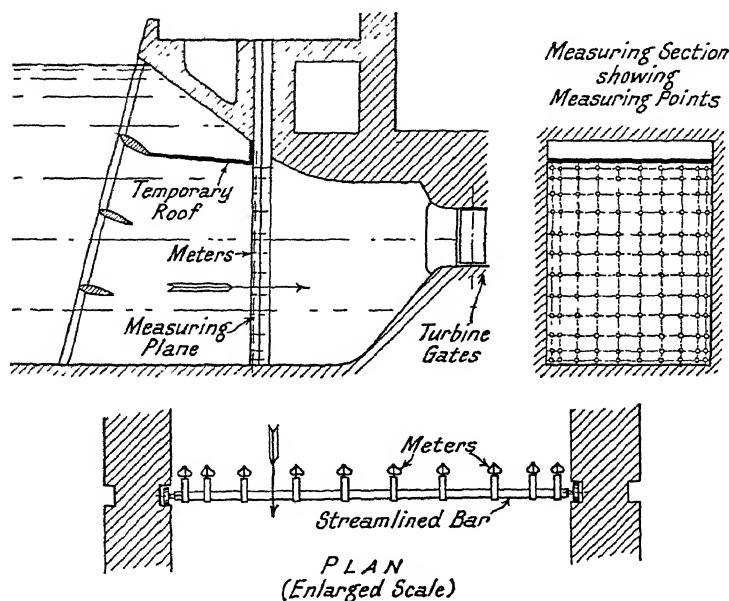


FIG. 94.—Multiple current meters in turbine intake.

hour or so, the velocity at more than a hundred points has been measured. After all these points are plotted on the scale drawing of the measuring section, a grid as shown in the diagram will have been formed; then follows the tedious work of assessing the area of each element of the cross-section, of computing from the chronograph strips and from the current meter rating curves the separate velocities, and finally of summing the products.

141. Variants of the Multiple-meter Technique. An example of the special treatment that is sometimes required is

illustrated in Fig. 95 (I), which shows the inlet to the Kaplan turbines in the Wettingen (Switzerland) power station⁽⁹⁶⁾ The flow filaments are here so steeply inclined that there can be no question of diverting them into a horizontal direction by any kind of temporary guide partitions, and it was therefore necessary to find out what the actual velocity directions were at various levels and to set the current meter axes at the corresponding inclinations. This was done by first exploring the entire measuring section with a light pivoted vane, revolving about a horizontal axis, which would swing accurately into the direction of the flow filaments and would transmit by electrical means the inclination to the observer above. The

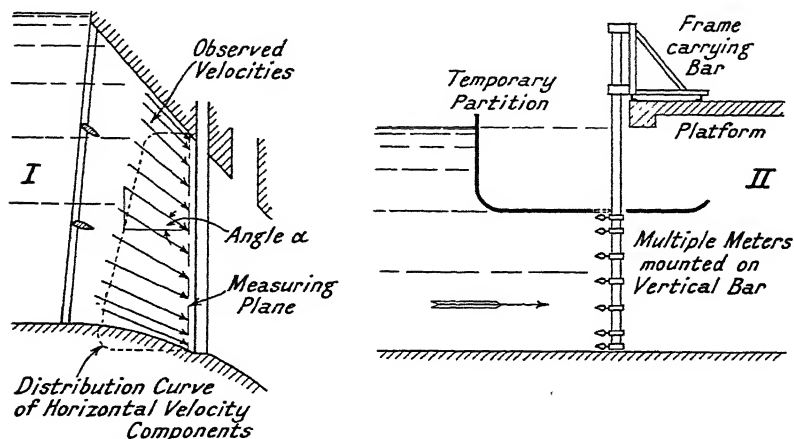


FIG. 95.—Multiple-meter technique for special conditions.

streamlined bar of the current meter frame (Fig. 94) could also be pivoted about its main axis, and by suitable mechanism it was tilted at each of the twelve measuring stations, so that the meters had the correct angle as determined by the preliminary exploration. It was finally an easy matter to calculate the true cosine components $v \cos \alpha$ (Fig. 95 (I)), and thus to compute the discharge.

Where, as at the hydro-electric station at Kembs (France),⁽⁹⁷⁾ the intake structure offers no completely suitable measuring section, it may be possible to use multiple current meters in the tail-race, provided that temporary stilling-racks can be built across the outlets of the draft tubes.

For smaller measuring sections such as occur at the inlet to low-head pumping stations, meters mounted on a vertical bar have been used,⁽⁹⁸⁾ the bar being clamped to a frame that can be traversed horizontally across the operating platform. In the installation shown in Fig. 95 (II), the purpose of the temporary partition was to increase the water velocity and thus make accurate measurement easier.

Although propeller meters have been used almost exclusively in the development of the multiple meter method of flow measurement, tests at pumping stations in Egypt have shown that if Price (cup) meters are the only ones available they also can yield consistent results.

142. Multiple Meters (continued). Some considerations that must be given full weight in preparing a current meter measuring programme are—

(i) The distribution throughout the measuring section of the individual measuring points. As regards the total number, this will depend upon the estimated regularity or otherwise of the flow: the more disturbed the flow appears to be, the greater must be the number of points. Rough guidance is given by the formula $N = 5 \text{ to } 8\sqrt{A}$, where N is the total number of measuring points, and A is the total area of the measuring plane in square feet. As regards the distribution of the points, they should be pitched more closely together near the boundaries than at the middle of the section (Figs. 94, 95) because the velocity variations are more rapid, and the velocity gradient is steeper, near the walls of the passage.

(ii) The stipulations concerning rating of the meters require scrupulous attention (§ 73), especially the need for rating the meter complete with the type of support that will be used in the test. Each individual meter must be specially rated both before and after the test.

(iii) To estimate whether, at any part of the measuring section, the obliquity of flow is great enough to influence the meter readings, screw and spoked types of meters may be arranged alternately along the supporting bar; and the divergencies between the observed velocities, when studied in the light of curves such as those reproduced in Fig. 52 (I), will enable the results to be corrected so as to give the true cosine component.⁽⁹⁹⁾

(iv) Only in the rarest instances ⁽¹⁰⁰⁾ is it practicable to check by absolute methods the registrations of multiple meters, but engineers who have had long and specialised experience in this field can produce evidence to show that if all possible care is taken the estimated error need not exceed ± 1 per cent. of the measured discharge.

METHODS EMPLOYING INJECTED SOLUTIONS

143. Colour-velocity Method. This method, apparently crude but sometimes capable of yielding fairly accurate results in conditions where pollution of the water is unobjectionable, may be looked upon as a type of float velocity measurement (§ 63), in which the "floats" are innumerable particles of dye or colouring matter. The pipe in which the flow is to be gauged should preferably be of uniform diameter and its end should be open so that the water can be seen running out; it should take its supply from an open tank or reservoir. Two observers are needed, each having a stop-watch; one of them notes the instant at which the colouring matter is injected at the pipe inlet, and the other watches the pipe outlet so that he can note the time when (i) the first sign of discoloration appears in the outflowing water, and (ii) the water again runs clear. Having thus found the mean time t for the colouring matter to traverse the pipe, it remains only to calculate the mean rate of discharge $q = \frac{V}{t}$, where V is the total volume of the pipe between the inlet and outlet stations.

The colouring matter, which may be a liquid dye or a dry powder, is enclosed in a glass, paper, or cardboard container tied to the end of a stick; the container is lowered into the mouth of the pipe and at zero time it is broken, so releasing the contents, by pushing the stick hard against the pipe wall. If the pipe inlet is inaccessible, a "lock" may be contrived at some suitable point in the pipe on the lines suggested in Fig. 93. By substituting in this lay-out a bottle of ink for the current meter, the act of injecting the dye is performed by jerking home the supporting rod against the pipe wall and smashing the bottle.

144. The Allen Salt-velocity Method (Principles). Prof. C. M. Allen, of Worcester, U.S.A., introduced a valuable

improvement into the injection method by using an electrical system of detecting the arrival at the downstream station of the dosed water, ⁽¹⁰¹⁾ and successive refinements have brought the procedure to such a point that in America its results are confidently accepted when making taking-over tests of large turbine units. In Scotland the Allen method has been applied in some of the stations of the Galloway Hydro-electric scheme. ⁽¹⁰²⁾ The detection apparatus depends upon the fact that the electrical conductivity of saline water is materially greater than that of pure water, and the essential element at

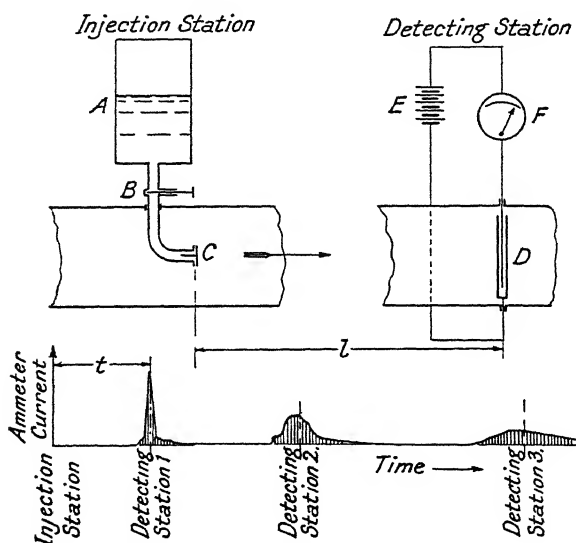


FIG. 96.—The Allen salt-velocity method.

the detection station is therefore a sensitive ammeter. Referring to the diagram, Fig. 96, the installation at the upstream or injection station comprises a container *A* in which a saturated solution of common salt is stored under compressed air pressure, a quick-acting valve *B*, and a spring-loaded automatic valve *C*. When the control valve *B* is rapidly opened and closed again, a dose of salt solution will be forced into the pipe and will be carried along with a mean velocity equal to the mean water velocity; but owing to the turbulence of the flow and the variable velocities throughout the pipe cross-section, the

salty water will quickly become more dilute and diffused throughout a greater and greater axial length of the pipe.

At the detecting station the ammeter F is coupled in circuit with a source of current E and with insulated electrodes D which are so spaced that when untreated water flows between them the ammeter registers a negligible current only. But when the dose of salty water arrives, a current flows between the electrodes in increasing strength and then dies away again; and the corresponding ammeter readings are recorded either autographically or from moment to moment by an observer. In any event time-current graphs are needed such as the one reproduced in Fig. 96; this relates to three detecting stations in series, and shows clearly the progressive dilution and dispersion of the dose as it passes downstream. The effective time t for the dose to traverse a length l is measured on the time scale of the chart in relation to the centre of gravity of the hatched "humps" on the chart. Sometimes it is found preferable to base the results on the time from one detection station to the next, rather than from the injection station to a single detection station.

In practice the pipe is hardly ever of uniform cross-section, and it is therefore necessary to measure its diameter at a number of points in order to assess the volume V between the two stations. This value, as shown in § 143, is used for computing the discharge $q = \frac{V}{t}$.

145. The Allen Method (Practice). Like the other methods outlined in this chapter, the salt-velocity system of measurement is an art as much as a science—an art which cannot be taught in a few paragraphs. But there are certain well-defined rules which will give general guidance (*see also* § 167).

Injection station. (i) The equipment for mixing and storing the salt solution may have to be fairly comprehensive, including perhaps two or three large vessels and containers, an air-compressor, and a feed-pump. An injection air-pressure of about 100 lbs./sq. in. may be aimed at. (ii) A single injection valve will only serve for quite a small pipe—say of 2 ft. diameter. Usually a number are needed, up to perhaps 24 for a 20-ft. diameter passage, these being evenly distributed

over the cross-section and connected to a bus-pipe. They should have rubber seatings and should close dead tight. (iii) The duration of injection need not be more than 1 to 2 seconds, and the moment of injection may be signalled automatically by the movement of the control valve, or by electrodes just downstream of the injection station.

Pipe. The salt-velocity method was specifically designed for flow measurement in the concrete inlet conduits (penstocks) of low-head turbines, and will give reliable results if the available length is only 60 ft. or so. Gradual and progressive changes of section are unobjectionable, except inasmuch as they increase the labour of accurately determining the volume between the two stations.

Detecting station. (i) Alternating current at about 110 volts is recommended. (ii) A single pair of parallel electrodes extending across the pipe is liable to over-estimate the discharge; bowed electrodes are therefore preferable, wider apart near the middle (pipe axis) than at the ends (pipe wall). (iii) Quite short electrodes held about midway between the pipe axis and the pipe wall give good results; alternatively, the short electrodes may be traversed across the pipe in the manner of Pitot tube orifices (§ 132), the method of insertion through the pipe wall being contrived in a similar way. The resulting distribution curve is not a true velocity distribution curve, but it does enable the mean velocity to be obtained.

METHODS ADAPTED SOLELY FOR HYDRAULIC TURBINES

146. The Gibson Inertia-pressure Method. This method, developed by Mr. N. R. Gibson, of the Niagara Falls Power Company,⁽¹⁰³⁾ enjoys just as high a prestige as the Allen method, and it is exceptionally interesting because of the manner in which it beneficially utilises a hydraulic phenomenon that more often appears in the light of a bugbear. The discharge in the turbine supply pipe is deduced from pressure measurements taken near the turbine inlet during the period in which the turbine regulating gear is gradually closed; and it is because of the inertia pressure or water-hammer deliberately generated in the pipe that the pressure readings have this special significance.

Let it be supposed that water is flowing from the forebay to the turbine with a mean velocity V through a supply pipe of length l and uniform diameter d (Fig. 97 (I)), the turbine control element, here represented by a valve, being set to maintain a steady load. The pressure head in the pipe at the point O will then be represented by the distance Oa , that is to say, by the static head h_s above the measuring point minus the sum $H_f + H_v$ of the friction and velocity heads in the pipe. If now the valve is closed in a period of 10 or 20 seconds, thus shutting down the unit, the resulting water-hammer will cause the pressure head at O to increase, there may temporarily be a rising hydraulic gradient as shown at b , and eventually the gradient will become horizontal and the static head h_s alone will be registered at the measuring point.

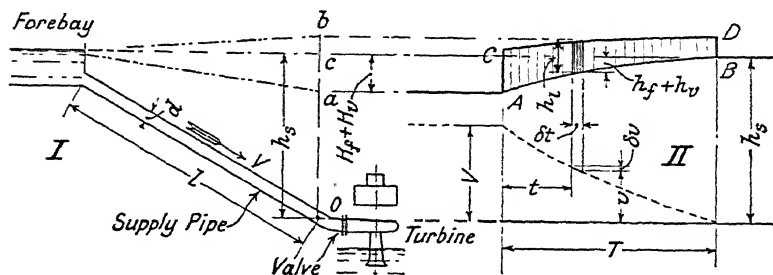


FIG. 97.—Theory of Gibson inertia-pressure method.

By plotting these changes of head on a time basis we produce a graph of the sort shown at (II), Fig. 97. So long as the turbine is running steadily the head-time curve will be level, at a distance $h_s - H_f - H_v$ above the base-line; the initiation of the valve closure will be represented by the sudden jump AC , and the drop DB will show that closure is complete and that the water column has been brought to rest in line T . On the same diagram it is helpful also to plot the velocity-time curve (broken line), for this reminds us of the manner in which the mean velocity gradually droops from its original steady value V down to zero. The problem now is to analyse the curve $ACDB$, and to make it yield the required original mean velocity V .

147. The Gibson Method (Theoretical Basis). Assuming that the velocity-time curve (Fig. 97 (II)) is known (although

in fact it is the whole object of the test to establish it), it is easy to find at any time t after the beginning of valve closure what the momentary velocity v is, and thus to calculate the corresponding values of the friction head h_f and velocity head h_v . Setting off the sum of these, $h_f + h_v$, below the line corresponding to the static head h_s , gives us a point on the curve AB which shows what the head at the measuring station O would have been if there had been no inertia pressure. By choosing other values for the time t , other points on the curve AB can be fixed, and thus the curve itself can be drawn. After any interval from zero time, then, the intercept between curves AB and CD will show the inertia head h_i , because the actual or observed head at the measuring station is represented by $h_s + h_i - h_f - h_v$.

Now the inertia head h_i may be calculated from the well-established formula

$$h_i = \frac{l}{g} \cdot \frac{\delta v}{\delta t} \quad . \quad . \quad . \quad . \quad (17)$$

where $\frac{\delta v}{\delta t}$ is the velocity gradient, or the slope of the velocity-time curve in Fig. 97 (II), during the very short interval δt ; and therefore

$$\delta v = \frac{g}{l} \cdot h_i \delta t.$$

Summing these small velocity increments, we have

$$V = \frac{g}{l} \Sigma h_i \delta t,$$

which means that the required original mean velocity in the pipe, V , is represented by the *area* of the hatched figure $ABDC$ multiplied by $\frac{g}{l}$.

The discharge q immediately before valve closure began was thus

$$q = \frac{\pi d^2}{4} \cdot \frac{g}{l} \times \text{area } ABDC \quad . \quad . \quad . \quad (18)$$

148. The Gibson Method (Practice). The elements of the apparatus by which the head-time curve is automatically traced are shown diagrammatically in Fig. 98. The head is measured by a U-tube mercury manometer (Fig. 6 (II), § 13 (i)),

directly connected to the measuring station O ; and by means of a lamp placed behind it, the movements of the mercury column are photographed on a sensitive film wrapped round a clockwork-driven drum. A pendulum swinging in the field of view of the camera serves to mark time-signals on the film.

With the turbine running under hand regulation only the gate opening is set to the specified amount and conditions are allowed to become stabilised; then the pendulum and the time-drum of the Gibson apparatus are set in motion, and immediately afterwards the order is given to the operator to close the gates: this he does with a steady movement, though without any attempt at complete regularity, in a total time which depends upon the water velocity and the length of the supply pipe. When the gates are fully closed the Gibson apparatus is left running until the oscillations of the mercury

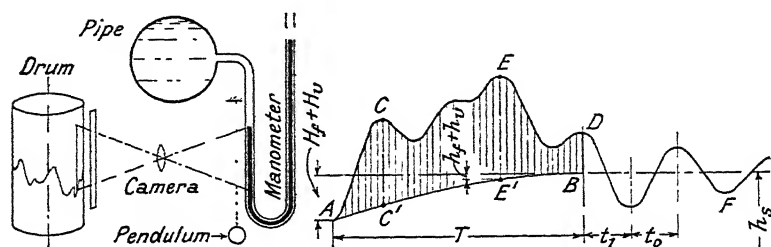


FIG. 98.—Gibson apparatus, and typical record from it.

column have quite subsided, whereupon the drum is stopped and the film is removed and developed. Meantime the turbine has thrown off its load, which has been picked up by the other units in the station, and is left running idly.

The difference between the actual head-time record, of which a typical one is reproduced in Fig. 98, and the ideal one, Fig. 97 (II), is accounted for by the inertia of the mercury column of the manometer, which superimposes its own wave system on the main diagram. It is first necessary to establish the point on the record corresponding to the moment of complete closure; by studying the residual oscillations from D to F it is found that this is the point D , for only to the right of this point is the wave-form symmetrical ($t_0 = t_1$, etc.). The next step is to trace the line $AC'E'B$ —a problem which was evaded in the preceding paragraph. It is not a serious one,

however, although possibly a little tedious. Selecting a point say, E at the peak of a wave, a likely-looking point E' immediately below it is fixed upon, and a provisional curve $AE'B$ sketched in. Since for practical purposes both friction and velocity heads in the pipe vary as (velocity)², it can be seen from the basic formula (18) (§ 147) and from a study of Fig. 97, that

$$\frac{h_f + h_v}{H_f + H_v} = \left(\frac{\text{area } EDBE'}{\text{area } AEDBE'A} \right)^2.$$

The position of E' is therefore adjusted until this relationship is fulfilled, other points such as C are likewise treated, and at last the final curve $AC'E'B$ is drawn. It only then remains to measure the hatched area $ACEDBE'C'A$ with a planimeter and to evaluate the discharge q from the basic formula (18), naturally taking account of the horizontal and vertical scales of the diagram.

149. The Gibson Method (continued). Some other matters for consideration are—

(i) The turbine gates when fully shut may be far from watertight, from which it follows that at the end of the Gibson test the water possibly still has a small residual velocity v_r . This velocity should be estimated by some suitable method e.g. noting the rate at which the supply pipe empties itself and should be added to the calculated velocity V to obtain the true original velocity.

(ii) If, as often happens, the supply pipe is not of uniform diameter, it must be divided for purposes of calculation into a number of lengths each of (assumed) uniform diameter. Denoting these short lengths by l_1, l_2 , etc., and the corresponding cross-sections by A_1, A_2 , etc., then the basic formula must be modified thus:

$$q = \frac{g(\text{area } ACEDBC'A)}{\frac{l_1}{A_1} + \frac{l_2}{A_2}, \text{ etc.}}$$

(iii) The *differential* system of measurement has certain practical advantages. Here the manometer is a differential manometer, connected to two points in the supply pipe from 30 to 50 ft. apart, with the result that the velocity-head term H_v is eliminated from the pressure diagram. Especially in

very large pipes this may represent 90 per cent. or more of the combined values $H_f - H_v$, and it follows that the line $AC'E'B$ (Fig. 98) will now be so nearly horizontal that errors in sketching its shape need be quite negligible.

(iv) The Gibson method has successfully withstood critical examination, both theoretical and practical, by experimenters in Europe who never disguise their preference for the current meter method of measurement. Among them is Dr. D. Thoma, of Munich, who has himself made valuable suggestions for minimising some of the troubles inherent in the original method. He devised a pressure recorder,⁽¹⁰⁴⁾ employing a piston working against a helical spring on the principle of Fig. 18, § 27, and a small mirror which deflects a ray of light, the inertia of the whole moving system being so small that all the uncertainty resulting from the oscillation of the mercury column was eliminated. In another form of German instrument, the Voith-Brecht, the lay-out resembles a conventional steam-engine indicator (§ 27).

150. The Use of Calibrated Turbine Control Gear. In most types of hydraulic turbine there exists a fixed relationship between the head, the speed, the gate opening, and the discharge, so that when once this relationship has been established a knowledge of the first three of these variables will enable the fourth, viz. the discharge, to be estimated pretty closely.

Pelton Wheel. Here the relationship is simple, because the discharge depends only on the head and on the position of the needle; thus for a given needle position the nozzle acts as a free-flow opening in which the ordinary square-root law holds good, that is, $q = \text{Constant} \times \sqrt{\text{head}}$. . . (formula (9), § 83). The head can be measured quite accurately, and the value of the empirical constant, for various needle positions, can be found by measuring the discharge in some other way, e.g. by current meter⁽¹⁰⁵⁾ (§§ 138, 139). Thereafter it suffices to read off the head and the needle position in order to know the discharge.

Francis or Propeller turbine. If N represent the speed of the turbine in revs. per min. and H is the net head, then for a given gate opening the law $q = K\sqrt{H}$ will only hold so long as the value of $\frac{N}{\sqrt{H}}$ is kept constant. But in practice this

condition will hardly ever prevail, because the turbine is tied to a fixed speed while the head, especially in low-head installations,

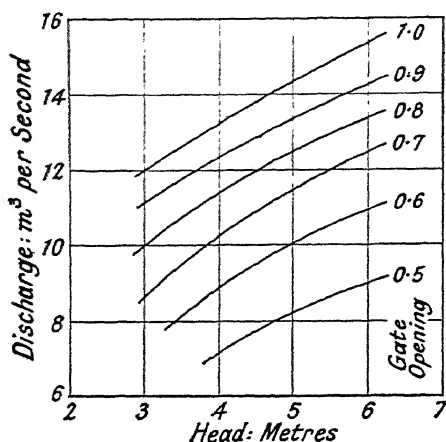


FIG. 99.—Head-discharge curves for Francis turbine of specific speed 100 (ft. units), running at constant speed of 105 r.p.m.

may vary by 50 per cent. or more. Each turbine running at a fixed speed will thus have for each gate setting a different head-discharge relation, and only if these are plotted on a single sheet, as in Fig. 99, will it be possible to read off, by interpolation, the discharge corresponding to a given set of conditions. A long and costly series of calibrations would be required to plot all these curves experimentally,

but they may be derived indirectly if other curves of turbine performance are available; also if model tests had been made to assist in the design of the turbine, the results of the model experiments, with the help of a few check full-scale calibrations, would give very useful guidance. But if, by whatever method, graphs such as Fig. 99 have been prepared, and if the head and the gate-opening of the turbine have been auto-graphically recorded, then at any future time the total flow that has passed through the machine in any specified period can be computed.

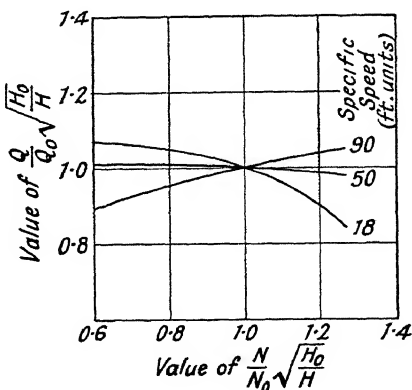


FIG. 100.—Typical head-speed relationships for Francis turbines at constant gate-opening.

Failing assistance from these sources, a single flow measurement will permit a rough estimate of the discharge at other

heads or speeds to be made if the curves in Fig. 100 are utilised. For a *given gate opening*, if Q_0 is the measured discharge under the normal head H_0 and the normal speed N_0 , then by interpolating between the curves according to the specific speed N_s of the turbine, the probable water requirement Q at any other speed N and head H can be found.

Example: When running under its normal head of 47 ft. at 0.8 gate opening, and at a speed of 125 r.p.m., a Francis turbine was found to use a measured discharge of 1620 cu. ft. sec. What would be the approximate discharge at the same speed and gate-opening, if the head were now 59 ft. ? The normal output of the turbine would be about

$$0.88 \cdot \frac{1620 \times 62.4 \times 47}{550} = 7600 \text{ h.p.,}$$

and therefore the specific speed would be

$$\frac{125\sqrt{7600}}{47^{\frac{3}{4}}} = 89 \text{ (ft. units).}$$

The required values to be used in Fig. 100 are

$$N_0 = 125, N = 125, H_0 = 47, H = 59, Q_0 = 1620.$$

The value of $\frac{N}{N_0} \sqrt{\frac{H_0}{H}}$ is thus $\frac{125}{125} \sqrt{\frac{47}{59}} = 0.89$.

From Fig. 100, we find from the curve $N_s = 90$ that the corre-

sponding value of $\frac{Q}{Q_0} \sqrt{\frac{H_0}{H}}$ is 0.975.

Consequently $Q = \frac{0.975 \times 1620}{0.89} = \text{about } 1780 \text{ cu. ft./sec.}$

151. Comparisons between Special Methods. In balancing the relative merits⁽¹⁰⁶⁾ of the four comparable methods of flow measurement, which may all have an accuracy within ± 2 per cent.—the Pitot tube traverse, the current meter traverse, and salt-velocity method, and the inertia-pressure method—one or other of the following considerations is likely to prove decisive: ⁽¹⁰⁷⁾

(i) If the spring-loaded piston type of pressure indicator can be relied on, the Gibson method is by far the most elegant, for the pipe-line is left entirely free and unencumbered, only a couple of holes need be drilled in the pipe wall, and the complete

registering apparatus is so compact that it can be held in the hand. But the technique of stopping the flow in order to measure it is undeniably drastic, and in practice the disposal of the load suddenly rejected by the turbine under test may not be altogether easy.

(ii) The equipment required for the salt-velocity method is rather formidable, and the essential parts can only be installed when the pipe is laid out of service and drained. The total cost of making a series of tests must consequently be quite considerable.

(iii) Both the inertia-pressure method and the salt-velocity method depend upon the careful measurement of the pipe cross-section at a number of points in its length.

(iv) Both of these methods share with the "Photoflow" method (§ 134 (iv)) the advantage of rapidity; two or three tests in succession from which a mean value can be obtained can be carried through in a quarter of an hour.

(v) When the Pitot tube or the current meter are used, only one measurement of the pipe area is necessary, but the measuring section should be judiciously chosen, a good distance downstream from bends, valves, or obstructions that might disturb the flow. Traversing methods are relatively slow, requiring from half-hour to an hour.

CHAPTER X

MEASUREMENT OF DISCHARGE IN OPEN STREAMS

(i) FREE-FLOW METHODS

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— Errors	162	— Validity	174

152. Conditions Prevailing in Stream Measurement.

From the point of view of size and scale the present chapter represents the culmination of the progression that has been carried through Chapters VII, VIII, and IX, and that, starting from quantity or total-flow meters designed in their smallest sizes for hardly more than a trickle of liquid, has now arrived at methods capable of gauging the flow of the Mississippi, the Nile, or the Ganges—flows that are reckoned in thousands of tons per second. From the point of view of basic principles a new element has to be introduced that itself complicates the measuring technique: it is the element of variability in the cross-section of the waterway. Whereas a pipe has rigid metallic or at least durable boundaries defining a cross-section which when once determined will remain invariable (except perhaps for the effects of corrosion or incrustation), the cross-section of a natural river will be subject to continual changes due to change of stage of the river, and possibly also to gradual alterations caused by silting or by erosion of its bed. Even if

the cross-section of the waterway at a given station does remain unaltered, its lack of any geometrical form and its variation from point to point along the length of the stream make the accurate estimation of its mean area a great deal more difficult than the measurement of the area of a cylindrical pipe. One other consideration is the personal safety of the operators themselves, which may make it imperative to suspend gauging operations in flood time just when the results would be of the greatest value. On the other hand, the effects of temperature, density and viscosity can now virtually be ignored, for the only liquid under consideration is water at atmospheric temperatures.

In this chapter only those methods are described which can be applied to rivers, streams, and canals flowing freely under their natural regime, the measuring appliances interfering in no way with the flow. Those methods which are applicable when the stream passes a control work such as a weir, regulator, or barrage, and which depend primarily on measurements of head, are discussed in the following Chapters XI and XII.

FLOAT GAUGING

153. Types of Floats. As suggested in § 63, a float is in reality no more than a device for making the movement of the water visible so that the speed with which the water moves down its channel can be timed. Although apparently so primitive an instrument it can still give useful service and has not been wholly superseded by the current meter. It is never used when the highest precision is demanded, however.

(i) *Surface floats.* These are intended to show the surface speed of the water. In the diagram, Fig. 101 (I), a bottle loaded so that the top of the neck is just visible is suggested; or round discs of wood will serve, or even oranges.⁽¹¹²⁾

(ii) *Subsurface floats.* The float itself is a canister or the like linked by a thin cord to a very small indicating float on the surface, Fig. 101 (II), the cord being adjusted so that the main float rides at a depth of $0.6d$ below the surface, where d represents the channel depth.

(iii) *Rod floats.* A parallel wooden rod about 1 in. square is loaded at its lower end so that in still water it floats upright

with its tip just visible above the water. When it is carried along by the current the total depth of immersion should be about $0.9 d$ (Fig. 101 (III)). To enable the length to be quickly adjusted to different depths of channel, the rod may be made telescopic. Alternatively a tin tube loaded with lead shot is useful.

(iv) *Captive float.* Recently developed to suit a special measuring technique, this float ⁽¹¹³⁾ has a buoyancy chamber which supports a canvas skirt having stiffening rings at intervals. The overall length of the float is adjusted so as just to clear the stream bed by "reefing" the skirt and clamping against the buoyancy chamber the rings corresponding to the reefs that have been taken in.

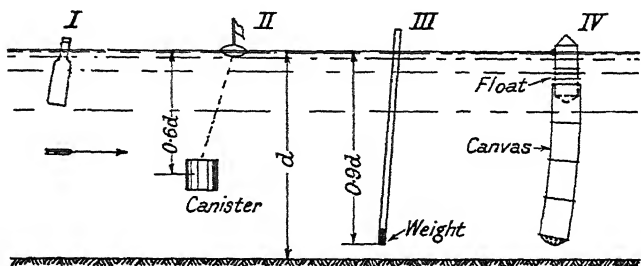


FIG. 101.—Types of float for stream gauging.

154. Timing the Floats. Two stations are selected a hundred yards or so apart, in a straight, uniform reach of the stream. The float is dropped into the water a little distance upstream of the upper station, and the moment at which it passes each station in turn is noted by an observer with a stop-watch. Sometimes the floats can be launched from a bridge spanning the stream, or else a moored boat may be used; or it may be necessary to lob the floats into the water from the bank.

In order to obtain a reasonable mean value for the velocity (which is represented by l , the distance between the stations, divided by t , the time of travel), a number of floats may be sent down in succession. Then to take into account the velocity variations across the width of the stream, four or more points are chosen uniformly spaced across the section, and at each of these points a set of floats is timed. Before or after

the float gaugings, soundings are taken so that the shape and the mean cross-sectional area of the waterway can be determined; then the total discharge is calculated by multiplying each element of the area by the corresponding mean corrected water velocity, and summing the products (§§ 163, 164).

A different method has been recommended⁽¹¹³⁾ for the "reefing" float (Fig. 101 (IV)). It is used as a captive float, always connected by a very light line to the boat containing the observers, nobody being needed on the river banks. After the boat has been manœuvred into the desired station in relation to the stream width, the float is released and the line allowed to run out from a reel, the observer braking the reel just enough to keep the line from becoming slack. At the end of the run, whose duration has been noted, the float is carefully wound in again. As the length of the run is read from markings on the line or on the reel, the operation is seen to correspond exactly, so far as *relative* velocities are concerned, to measuring a ship's speed by the use of a floating log and log-line.

155. Accuracy of Float Measurements. Apart from the reefing or captive float, concerning which sufficient information is not yet available, the *rod* float (Fig. 101 (III)) is usually considered to give the most reliable results. When adjusted to the specified depth of flotation its timed speed agrees fairly well with the mean water velocity throughout the effective area swept, and thus the error in computing the discharge need hardly be more than ± 3 to 5 per cent. The chief practical difficulty is that the beds of natural streams are rarely uniform enough to allow the necessary small clearance between the lower end of the float and the bed; the immersion has then to be set to a smaller value than $0.9 d$ to avoid the risk of the float running aground or dragging here and there.

In using *sub-surface* floats (Fig. 101 (II)) the assumption is also made that the float runs at the mean speed of the water in the area swept through, but the results it gives are accepted with less confidence than those of rod floats.

The *surface* float obviously moves at a greater speed than that of the mean water filament below it, and the ratio between the two speeds—on which the whole value of the

gauging depends—can hardly be more than guessed at. This ratio

$$\frac{\text{Mean velocity over vertical}}{\text{Timed surface float velocity}}$$

increases as the water depth increases, and diminishes as the roughness of the channel bed increases,⁽¹¹⁴⁾ between limits of about 0.82 and 0.92. The ratio is also seriously affected by the wind—whether the wind is blowing upstream or downstream, etc.; and even a side wind is disturbing because it blows the floats off their course. Unless, therefore, the gaugings can be supervised and interpreted by unusually experienced officials, or unless they can be checked by some other measuring system, the use of surface floats may involve errors up to ± 8 or 10 per cent. But if a quick emergency gauging must be made, when any kind of result is better than none, then a single timed run of a surface float down the middle of the stream will give a rough notion of the discharge from the relationship

$$\frac{\text{Mean velocity over the entire cross-section}}{\text{Timed surface float velocity along centre of stream}} = \text{about } 0.84.$$

CURRENT METER GAUGING

156. General Principles. The current meter is nowadays recognised as the standard instrument for measuring the discharge of rivers and canals; its construction and calibration have already been outlined (§§ 70-77) so that the particular problems to be faced in stream gauging can at once be discussed.⁽¹¹⁵⁾

As in all current meter measurements (e.g. §§ 138-142), the first step is to establish the principle on which the meter will be presented to one point after another at the selected station in order that the velocity distribution over the whole cross-section of the waterway can be properly explored. The usual system is shown in the diagram, Fig. 102. The transverse surface width of the stream, B , perpendicular to the mean velocity direction, is divided into a number of elements of (normally) uniform width b , and verticals such as aa are

imagined to be dropped to the stream bed. Velocity measurements are then confined exclusively to these verticals, which are pitched sufficiently closely to give an adequate picture of the flow. This pitch b may vary from 2 ft. for small channels up to 20 ft. or more for large rivers and canals.

By setting the current meter in turn at various points along

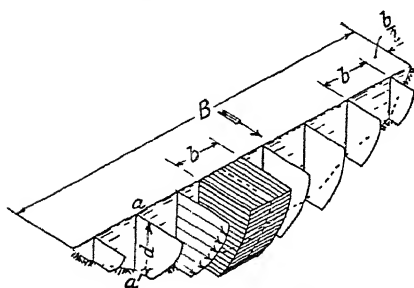


FIG. 102.—Subdivision of stream cross-section.

each vertical and observing the speed, velocity distribution curves can be plotted, and the mean velocity in each vertical computed; and if the mean velocity v_m is multiplied by the corresponding area of the cross-section, the element of discharge $b \cdot d \cdot v_m$ associated with that vertical can be found.

In the diagram this element is represented by the volume of the solid distinguished by hatching. The total stream discharge is the sum of the individual discharges, i.e.

$$q = \Sigma b \cdot d \cdot v_m.$$

It should not be forgotten that the measurement of the successive depths d is just as important a part of the gauging operation as the measurement of the velocities.

157. Estimation of Velocity Distribution in Verticals.

For many reasons it is desirable to carry through the gauging as quickly as possible, not only to economise the time and labour of the observers, but because what they are seeking—the momentary rate of flow of the stream—is itself a fugitive quantity; the river, that is, may be changing its stage (rising or falling) so rapidly that by the time the observers have made their last reading the first ones may be valueless. Consequently it is often impracticable to make so many velocity determinations along each vertical that the distribution curve can be definitely established, as in Fig. 103 (I), although this is an ideal to be aimed at when possible. Instead of this *multiple-point* method, two or only one velocity measurement need be made, which may yield the required value of the mean

velocity in the vertical. v_m , accurately enough for most ordinary purposes.

The arithmetic mean of *two* observations, one at 0.2 of the depth d and one at 0.8 of the depth (II in the diagram), is almost exactly equal⁽¹¹⁶⁾ to the mean velocity v_m , viz.

$v_m = \frac{v_1 + v_2}{2}$. If *one* observation is made at a depth below

the surface of 0.6 d (III), this measured velocity v will rarely differ by more than 1 or 2 per cent. from the mean velocity v_m . If the *half-depth* velocity is measured, then $v_m = 0.96 v$ within the same limits (Fig. 103 (IV)).

In the *integration* method the meter is steadily moved up or down the vertical at a uniform rate while observations are being made, and thus its mean speed during this period will give a true measure, without correction, of the mean velocity v_m . But this procedure is only to be recommended with the propeller type of meter; it should not be attempted with cup meters unless the vertical rate of movement is very small compared with the water velocity (§ 75).

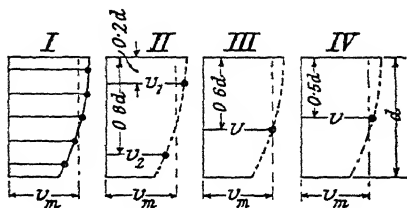


FIG. 103.—Estimation of mean velocity in a vertical.

The less favourable the gauging site and the more uncertain the conditions there, the less reliable do the two-point and one-point methods become. But if a few series of multiple-point observations can be run off, they will fix the characteristic shape of the velocity distribution curves at that station and thus supply the necessary corrections by which the simpler methods can thereafter be used with confidence.

If the shape of the section departs widely from that of a normal stream, it may be necessary to distribute the measuring points on the principle suggested in § 142 (i).

158. Choice of Gauging Site. Measuring procedure can be simplified and its value enhanced by careful choice of the site where routine observations will be carried out. It has frequently to be borne in mind that the current meter measurements themselves are only a means to an end, the ultimate aim

being to calibrate some other device which will subsequently give the required information about the flow of the stream. As a rule this secondary device is a staff gauge or its equivalent (§ 5), whose readings will permit a stage-discharge curve to be plotted (§§ 172-174). The ideal gauging site should therefore fulfil the following requirements :—

(i) It should be near the downstream end of a long, straight, uniform reach of the river or canal, beyond the zone of excessive turbulence created by flow through sluices or over weirs.⁽¹¹⁷⁾

(ii) The cross-section should be regular and symmetrical without gently-shelving banks.

(iii) The cross-section should be stable, not liable to be influenced by erosion or silting.

(iv) The site should form a true *control section* ; that is, there should be an invariable relationship between the water level and the discharge. This condition will only hold good if the site is beyond the range of the backwater created by changes in the regime downstream, e.g. the influx of a variable tributary stream, the heading-up of the main stream by a movable weir or regulator.

(v) The site should be reasonably accessible, preferably by road ; sometimes, evidently, this is a counsel of perfection.

(vi) The mean velocity should not be less than about 2 ft./sec.

159. Supporting the Meter. (i) **Rod support.** Having defined the gauging site by a post or beacon on either bank so disposed that the line joining them is truly perpendicular to the mean direction of flow of the stream, a decision must be made, based on the characteristics of the site and of the stream, concerning the spacing of the verticals and the positions the meter is required to take up on those verticals. The mechanical problem then arises of actually holding the meter in those positions ; suitable tackle must be devised for locating the meter both transversely and vertically, and for enabling it to resist the thrust of the water on it. The insulated cable which transmits electrical impulses from the meter to the signalling apparatus has also to be looked after.

Various types of *rod support*, suitable for relatively small streams, are sketched in Fig. 104 ; in all of them the meter is

rigidly fixed and therefore a tail is unnecessary. Propeller meters are held in this way more often than cup meters.

(I) Here the graduated rod has a spike which can be driven into the stream bed and a sole-plate or foot to define the bottom of the vertical. An observer wearing wading-boots stands in the water during the observations and carries the rod from point to point.

(II) This is an excellent system if there is a light platform or bridge which crosses the stream without interfering with the flow. The graduated rod can be traversed up and down guides in a bracket by means of a winch, and when readings in one vertical are finished the observer shifts the bracket along to the next one.

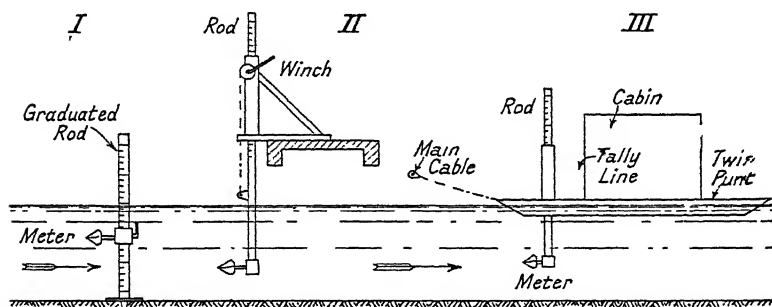


FIG. 104.—Rod-supported meters.

(III) The observers and all their gear are now accommodated on a floating platform—in the diagram (Fig. 104) two punts with a little deck-house are shown.⁽¹¹⁸⁾ As in method (II), the rod slides in vertical guides, but this time the question of keeping the meter in its appointed place needs more attention. A wire rope is stretched across the stream just upstream from the gauging plane, and by paying out or hauling in the mooring-line the platform can be manœuvred so as to bring the meter correctly into the gauging plane. Suitable tackle permits the platform also to be warped across the stream, from one vertical to the next, a light, graduated tally-line running from bank to bank indicating where the verticals are.

160. Supporting the Meter. (ii) **Cable suspension.** When used for gauging broad canals and rivers the current meter must almost invariably be hung from a stranded cable.

This implies that: (a) the meter must have a tail to keep it facing the current (Fig. 46); (b) in order to resist the thrust of the water and to prevent the meter from being swept too far downstream, it must have either a heavy sinker or a guy-wire; and (c) the vertical position of the meter can only be ascertained by reference to graduations on the winch-drum which winds in the supporting wire. Another rather important feature of cable suspension is that it puts the cup and the propeller meter on an equal footing; it is in such conditions, indeed, that the cup meter has built up its reputation.

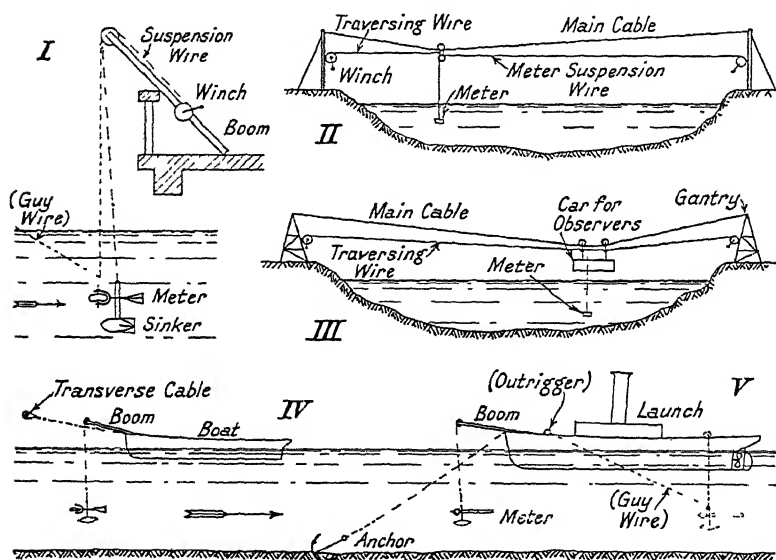


FIG. 105.—Cable-supported meters.

The following notes refer to the respective diagrams in Fig. 105:—

(I) If a platform or bridge thrown across the stream is available (although more likely than not the disturbance set up by the abutments will rule out such a site) a light boom will hold the winch and will make matters very easy for the observers. It might be feasible to rig a guy-wire from two points on the bank, a little distance upstream.

(II) The meter is here suspended from a carrier running on an overhead cable stretched from bank to bank.⁽¹¹⁹⁾ A winch

on one of the supporting posts traverses the carrier to and fro across the river, and a winch on the other post hoists the meter up and down.⁽¹²⁰⁾ Trees may sometimes be found which will serve as the supporting posts.

(III) This more elaborate variant of system (II) has the advantages that the observers sitting in the car are near their work and that the long vulnerable piece of electric cable between the meter and the bank is cut out. Rod-supported meters can sometimes be used with this equipment.

(IV) The only material difference between this system and the one shown in Fig. 104 (III) lies in the mounting of the meter; the boom has a winch just as it has in (I), above. Any suitable locally-built boat can be adapted for use at the gauging site; or a specially designed platform supported on two sheet-metal cylindrical buoyancy chambers, serviceable for sheltered waters, may be so lightly built that it can easily be transported from site to site on a light lorry.

(V) Navigational requirements often forbid the stretching of a cable across the waterway to be gauged, and for really large rivers the whole equipment would in any event have to be so substantial that the cost would mount up prohibitively. The observers have thus no other choice than to do their work in a boat which, during observations, must either be moored to a buoy or actually anchored. A power-driven boat will be more agreeable at all times, and may be indispensable in bad weather or in flood-time. To prevent risk of the current meter or its wire fouling the anchor chain, the meter may be hung from an outrigger well out on the beam, and guyed from another outrigger further forward. The position of the launch is established by means of sextant bearings taken on a pair of well-spaced beacons on each bank.⁽¹²¹⁾

161. Gauging Procedure. For routine gauging operations printed forms are usually available on which the observations can be recorded. The general information to be entered on the form includes: Names of observers; Date and time; Name or description of gauging site; Particulars of wind, weather; Type and reference number of current meter; Readings, preferably at various times during the gauging, of the staff gauge or other water-level gauge at the site. Then as the actual gauging proceeds the observers note down: Transverse

position of the vertical with respect to the bank ; Depth of water at vertical ; Depth of current meter below water surface ; Revolutions of meter per minute, or time for a standard number of revolutions.

If the two-point or one-point system is in use (§ 157) it is manifestly necessary to measure the depth at the vertical before the current meter can be located at the stipulated point at two-, five-, six-, or eight-tenths of the depth below the surface. Sounding methods have been described in § 6. The sounding rods or sounding wires there mentioned are both very suitable for present conditions, depending upon whether the water is quiet and shallow or swift and deep ; or a cable-suspended meter may itself be used for sounding. First the meter is lowered until the sinker just touches the water, and the reading on the winch is taken ; then more cable is paid out until the weight can just be felt to touch bottom, whereupon the second reading minus the first gives the water depth. Sometimes the sinker has a small contact pad which gives an electrical signal when it touches the channel bed.

The working depth of the meter is regulated in a similar way. The scale on the winch-drum is read when the axis of the meter is just in the water surface, and then the requisite length of cable is paid out.

162. Avoidable and Unavoidable Errors. Windy weather may fairly be classed as a possible cause of error which can hardly be avoided except by waiting for the wind to drop. Especially in shallow streams the wind may appreciably affect the velocity distribution, and it certainly makes sounding more difficult. But the worst effect is felt when observations are taken from any kind of floating platform, for not only does the motion of the water and of the boat make it still more troublesome to decide just where the mean water surface is, but the up-and-down motion imparted to a *cup* meter will seriously affect its registration.⁽¹²²⁾

Here, at any rate, is an error for which there is no excuse when the water is calm ; the operators must remain perfectly still so that the boat may remain quite steady while the current meter is running.

Another error that it is easy to avoid is that of timing the revolutions of the meter over too short a period. Anyone

engaged on such work has only to look at the water to see that it does not move in a smooth, regular way, but rather comes along in an irregular progression of swirls, "boils," and surges. These impart to the wheel of the meter a varying rate of revolution, and thus the desired *mean* speed can only be found by allowing the meter so long a run that the irregularities are averaged out. One minute may be considered the minimum period, but a period of two or three minutes is better.

Blame for using a damaged instrument need not always fall on the observer. The meter may have "lost its rating" from some imperceptible cause, and a meter that is obviously out of order may have to be put right by any rough field treatment that is available. But any such adjustment should be noted on the observation sheet so that the discharge computation may be based on the *new* rating of the meter, after its return to the rating station.

163. Computing the Discharge. The precise estimation of stream discharge as found from current meter observations really involves the determination of the volume of a solid (Fig. 102) having a flat top, a vertical face, and a curved side forming the envelope of the various velocity distribution curves. This volume can be expressed in the form

$$q = \Sigma b \cdot d \cdot v_m \dots (\S 156),$$

and the practical problem is to choose an acceptable approximation which takes account of the fact that the distance between the verticals, b , is very far from being negligibly small compared with the total width B . The graphical method described in the next section involves fewer assumptions than any other, but it is rarely found convenient in practice. Of the various algebraic formulæ that are available for evaluating q , the simplest is often sufficiently accurate if the stream cross-section and the velocity distribution are reasonably regular. It assumes that changes in depth from one vertical to the next occur in steps, and therefore that each element of the cross-section is a rectangle of area $b \times d$. As the following example shows, the computation is quite straightforward. In this instance it will be noticed that near the banks the verticals are spaced more closely than in midstream. Velocity measurements were made at half-depth, because it is easier to divide

the sounding by two than to multiply it by six-tenths. Another interesting point is the variation in the speed of the current meter during successive minutes (§ 162).

TABLE OF CURRENT METER OBSERVATIONS AND COMPUTATIONS

(Instrument—Price Meter.)

(A) Distance from Bank (measured at water surface) (metres)	(B) Mean Distance between Soundings (metres)	(C) Sounding (metres)	(D) Area of Section = (B) × (C) (sq m)	(E) Revolutions of Current Meter in One Minute at Half Depth.			(F) Mean r.p.m. of Meter at Half Depth	(G) Corresponding Mean Velocity at Half Depth (from rating curve) (m./sec.).	(H) Mean Velocity over Section = $0.96 \times (G)$ (m./sec.)	(K) Discharge in Section = (D) × (H) (cub m./sec.).
				1	2	3				
0	—	—	—	—	—	—	—	—	—	—
4	4.0	1.90	7.6	38	39	39	38.7	0.439	0.421	3.20
8	6.0	3.40	20.4	47	48	45	46.7	0.528	0.507	10.35
16	8.0	4.10	32.8	56	58	57	57.0	0.644	0.618	20.28
24	8.0	4.00	32.0	56	54	55	55.0	0.621	0.596	19.08
32	8.0	4.10	32.8	61	60	63	61.3	0.691	0.664	21.78
40	8.0	3.90	31.2	61	59	62	60.7	0.684	0.656	20.46
48	8.0	4.00	32.0	56	57	58	57.0	0.644	0.619	19.80
56	6.0	4.50	27.0	58	55	56	56.3	0.635	0.610	16.48
60	4.0	3.50	14.0	42	43	43	42.7	0.484	0.465	6.51
64	4.0	1.70	6.8	35	35	33	34.3	0.390	0.375	2.55
68	—	—	—	—	—	—	—	—	Total	140.49

Canal Discharge = 140.5 cubic metres per second.

164. Graphical Determination of Discharge. The graphical evaluation of the function $q = \Sigma b \cdot d \cdot v_m$ is known as Harlacher's method; it has the advantage over arithmetical solutions that it provides a much clearer picture of the shape of the cross-section and of the velocity changes across it. Fig. 106 shows the graphical method applied to the basic data used for the tabular solution in the preceding Section. The soundings d are first set off to scale below the base-line, as at aa' , and the mean velocities v_m are set off above the base-line, as at ae' , the lower broken curve thus representing a transverse section of the bed and the upper broken curve

the distribution of mean velocities. To find the product of $a a'$ and $a e'$, any appropriate distance $ae = k$ is marked off along the base-line, then aa'' is struck off equal to $a a'$, and $a''e''$ is drawn parallel to ee' . The intersection e'' on the vertical is a point on the discharge curve. Repeating on all the other verticals, always keeping the same value of k , a series of points such as e'' is obtained, and a smooth curve through these points (*full line in the diagram*) is the discharge curve whose ordinates at any point are proportional to discharge per unit width of channel. The area enclosed between the curve and the base-line thus represents the total stream discharge, and the desired numerical value is found by measuring

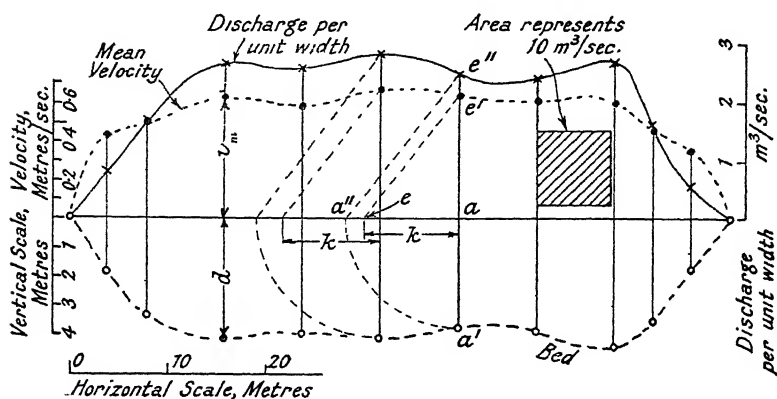


FIG. 106.—Graphic determination of discharge.

the area of the diagram with a planimeter and multiplying it by a constant depending on the length and velocity scales and on the distance k .

Whether the graphical integration is used or not, it is well worth while plotting the channel cross-section after each gauging so that a record of changes in the gauging section may be filed and compared.

OTHER GAUGING METHODS

165. The Pitot Tube. Although the Pitot tube (§ 64) was at one time extensively used for stream gaugings it suffers from two disabilities in comparison with modern methods ;

(i) the differential head generated in normally-flowing rivers and canals is too low for reliable measurement, and (ii) the problem of supporting the tube is troublesome when the river is wide or deep. But in swiftly-flowing artificial waterways, and especially in laboratories and research institutions, the Pitot tube is extremely useful. Here the channel width may be only a few feet, and thus offers no difficulty to the design of a graduated transverse supporting bar which, in conjunction with a graduated vertical bar having suitable clamps, permits the Pitot tube orifices to be accurately set and held at any position. With such equipment the velocity distribution in, e.g., the nappes of weirs, in the throats of flumes, and in the vents of model sluices can very conveniently be mapped.

The most elementary type of tube (Fig. 41 (Ia)), drawn and bent from a single length of glass tubing, is often perfectly satisfactory, but as a rule the combined types are more suitable—either the impact-trailing arrangement (III), or the impact-static arrangement (IV). Discrimination must be exercised here, in view of the rapid changes in velocity and in pressure distribution that are likely to occur in such abnormal conditions. The differential head may be read on a double-column manometer (Fig. 9 (I)), having a suction pump or the like so that the water columns can be drawn up to a suitable height.

A recent modification of the impact-trailing Pitot tube adapting it for low-velocity flows in open streams—down to 0.15 ft./sec.—has given promising results; ⁽¹²³⁾ the differential head is allowed to create a through current of water through the apparatus, and this very small “shunt” current is measured by a kind of variable-area meter (§ 135) graduated in units of velocity.

166. Measurements based on Surface Slope. By the use of the Chezy formula $v = C\sqrt{mi}$ it would appear that the mean velocity across the whole section of a stream could be calculated from a knowledge of the dimensions of the section and of the longitudinal slope i , and that in consequence the discharge $q = Av$ might be found. In practice it is rarely possible to obtain in this way more than a very rough estimate of the discharge because of the difficulty of measuring the slope accurately. The term i represents $\frac{h}{l}$, that is, the fall in surface

level h in a length l of waterway, and as the only available straight, uniform length may give a value l of a few hundred yards only, the drop h may be no more than a few inches. Moreover, the effect of the surging irregular motion in open streams may be such as to cause fluctuations in h of the order of 20 per cent. or more during any one period of observation. There still remains the problem of assessing the mean cross-section of the waterway A and the wetted perimeter P in order to determine the hydraulic mean depth $m = \frac{A}{P}$; and there is the

final uncertainty of choosing the right value for the Chezy coefficient C which itself depends on the roughness of the channel bed, and on the values of m and of i .

In especially favourable lengths of artificial canals these various difficulties have been overcome sufficiently to make it possible to construct an automatic discharge recorder; ⁽¹²⁴⁾ float-operated mechanisms at each of two stations a suitable distance apart are electrically interconnected, and by means of cams shaped to suit the particular characteristics of the gauging length the flow equation is mechanically solved and the result drawn by a pen on a clock-driven chart.

The occasions when the slope-area method gives information which, though crude in the extreme, may yet have value occur during floods, especially if the floods are so abnormal that the water rises far outside the range of the hitherto accepted stage-discharge relationship. ⁽¹²⁵⁾ From the high-water marks left by the receding river the necessary values of A , P , and i can be roughly estimated, although no more than a guess concerning the value of the coefficient C can be made, for when the river is running out of its banks C will certainly have a sub-normal value.

167. The Allen Salt-velocity Method. The basic principle of the salt-velocity method (§ 144) may quite well be applied to stream gauging, but naturally the practical possibilities are limited by the cost of the equipment, which is already considerable enough even when gauging the relatively smaller flows in closed conduits. There is the added drawback of the great amount of labour involved in determining the exact volume enclosed between the injection station and the detecting station—a labour which can only be contemplated if the stream is an artificial canal with lined banks.

When tested against the volumetric method at the Walchensee Research Station,⁽¹²⁶⁾ the salt-velocity method gave good results, and very complete acceptance tests for turbine units in America ⁽¹²⁷⁾ have been made on a large scale, using a length of about 450 ft. of the head-race canal. In order to measure discharges of the order of 50 to 80 tons per second during a series of tests lasting for two days, ten tons of salt in the form of a concentrated solution were injected through a system of thirty-eight pop-valves, and the passage of the slightly saline water at the detecting station was observed by means of thirty pairs of vertical steel electrodes. The results were compared with current meter gaugings and were used to calibrate "sub-Venturi" tappings in the turbine scroll-casings; thus the published description of the tests is of unusual interest.

168. Chemical Gauging Methods. These methods have the great attraction that they are wholly immune from the effects of just those factors which contribute to the uncertainty of other methods, e.g. excessive turbulence, irregularity of gauging section, difficulty of taking soundings, doubts concerning rating results, and so on. The two classes of measurement are thus complementary: everything that tends to make the flow smooth and regular is favourable to current meter and similar methods, and everything that tends to turbulence and irregularity favours the chemical method.

To gauge a stream by the chemical method two stations are chosen—an upstream "dosing" station and a downstream "sampling" station—in the most tortuous reach of waterway available, Fig. 107 (I); if the reach includes a waterfall, rapids, a weir, a turbine, or anything that thoroughly mixes the water, so much the better. At the dosing station a strong solution of some cheap chemical salt, made up to a known concentration, is run into the stream at a measured rate; at the sampling station samples of water are taken from the stream at different points of the cross-section: and that completes the work in the field. Later on these samples are examined in order to find the proportion of chemical they contain, and the stream discharge is finally deduced by comparing the concentration of the injected solution with the very much weaker concentration of the dosed river water.

Evidently the whole success of the procedure depends on finding a substance so cheap that the gauging authorities can afford to throw away large quantities of it into the river, and yet of such a nature that very small proportions can be detected with accuracy by observers unfamiliar with chemical analysis. Common salt, calcium chloride, caustic soda, and sulphuric acid have all been tried; ⁽¹²⁸⁾ but because it is inexpensive, harmless and easy to buy, common salt is now nearly always preferred.

To ensure the indispensable mixing of the chemical solution with the stream water the "dose" may be fed through a manifold pipe having openings evenly distributed over the cross-section of the stream; to ensure that a true mean sample can be tested, individual samples should be taken in glass bottles from a number of suitably-spaced points at the sampling station, and mixed together.

169. Salt-titration Method. When salt is used the chemical gauging method is often known as the salt-titration

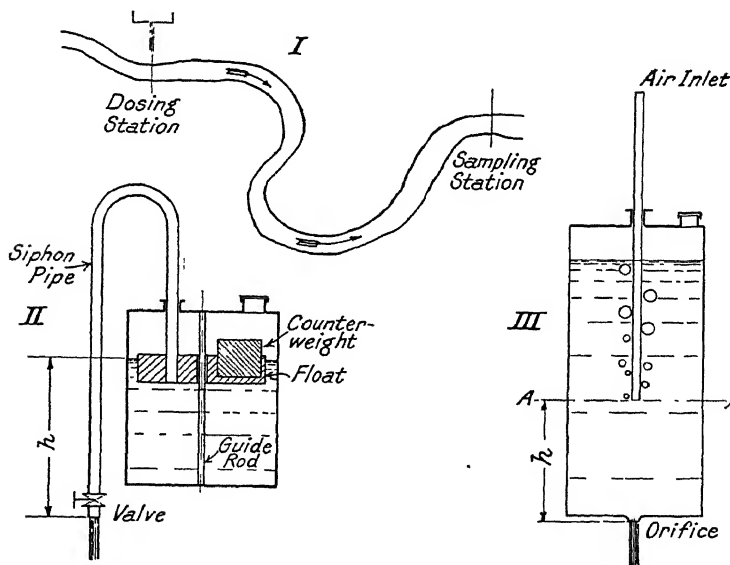


FIG. 107.—Salt-titration method.

method, which must be carefully distinguished from the entirely different salt-velocity method. Enough salt solution should be

prepared, of a strength of about 1 part salt to 4 parts water by weight, to give an estimated concentration at the sampling station not weaker than 1 in 30,000, and to last for at least ten minutes. Suggestions for feeding this solution at the requisite uniform rate into the stream are given in Fig. 107. A floating siphon pipe (II) maintains a uniform head h on the gauging orifice, or alternatively an airtight container (III) is used which also ensures a constant head. The rate of discharge can be adjusted in the one system by regulating on the valve and in the other by drawing in or out the air inlet pipe. More elaborate equipment is required for large-scale gauging, but in any event provision must be made for volumetrically checking the rate of discharge and for accurately measuring the concentration of the solution.

170. Details of Titration. In the following summary of the process recommended ⁽¹²⁹⁾ for determining the concentration of the salt in the water taken from the sampling station, it will be seen that reference is made also to samples of undosed water taken upstream of the dosing station; this is necessary in cases where the natural salt content of the river water is appreciable.

Let k_0 = weight of salt in unit volume of undosed water,
 k_1 = " " " " " salt solution,
 k_2 = " " " " " dosed water,
 q = rate of discharge of salt solution,
 Q = " " " stream.

Since the total weight of salt leaving the dosing station in unit time must be the same as the weight arriving at the sampling station in unit time, we may write

$$Qk_0 + qk_1 = (Q + q)k_2,$$

whence

$$Q = q \left(\frac{k_1 - k_2}{k_2 - k_0} \right).$$

Mohr's titration method is used to obtain the relative salt concentration in the three sets of samples. These are either diluted with distilled water, or evaporated, as the case may be, until 5 c.c. of the resulting liquid contains not less than 0.014 gm. of salt. To each of the 5 c.c. "adjusted" samples so obtained, five or six drops of a cold saturated solution of

potassium chromate are added. The actual titration may now be undertaken: a solution of silver nitrate, of a strength of 2 gm. per litre of distilled water, is run from a burette into the "adjusted" samples. At a critical point the yellow colour of the potassium chromate suddenly turns to a distinct red; the volume of silver nitrate solution required to bring this about must be carefully observed.

It is finally an easy matter to work out what volume of silver nitrate solution would be required to titrate 1 litre of each of the *original* three sets of samples. These volumes, V_0 , V_1 , and V_2 , are clearly directly proportional to k_0 , k_1 , and k_2 , and hence

$$Q = \text{discharge of stream} = q \left(\frac{V_1 - V_2}{V_2 - V_0} \right).$$

The salt-titration method consistently emerges with credit from comparative tests,⁽¹³⁰⁾ and in its own field it should give results as reliable as those from carefully-controlled current meter gaugings, viz. an accuracy within ± 2 per cent.

171. Electro-chemical Gauging. An interesting combination of the salt-titration and salt-velocity methods has been proposed⁽¹³¹⁾ in which measurements of the electrical conductivity of the dosed water are used not merely to detect the salt but to estimate its concentration. At the dosing station the procedure is simplified because it is necessary to know only the total volume of brine fed into the stream during the test, without the need to keep the rate of feed uniform. The equipment at the downstream station, like that at the detecting station in the Allen method (§ 145), permits a curve to be plotted between time and conductivity, but now it is the *area* of this curve which forms the basis for the discharge computation; moreover, the electrodes are immersed not in the main stream but in a shunt circuit on shore which is maintained by a hand-pump continuously drawing water from the stream through a suction pipe moved to and fro across the gauging section.

When the possibilities of this combination are developed, it may be preferred to the straight titration method by engineers who are more at home among electrical measurements than among chemical ones.

RECORDING OF DISCHARGE OBSERVATIONS

172. Purpose of Stage-discharge Records. There is not one of the gauging methods discussed in this chapter—nor do any exist—that is not to some extent either costly, laborious, or uncertain. The results that they offer consequently represent an investment of time and money that will only be profitable if they yield in the future a steady return of useful information about the flow of the stream past the gauging site. This can best be ensured by plotting for each site a *stage-discharge* curve having as co-ordinates the stage of the river

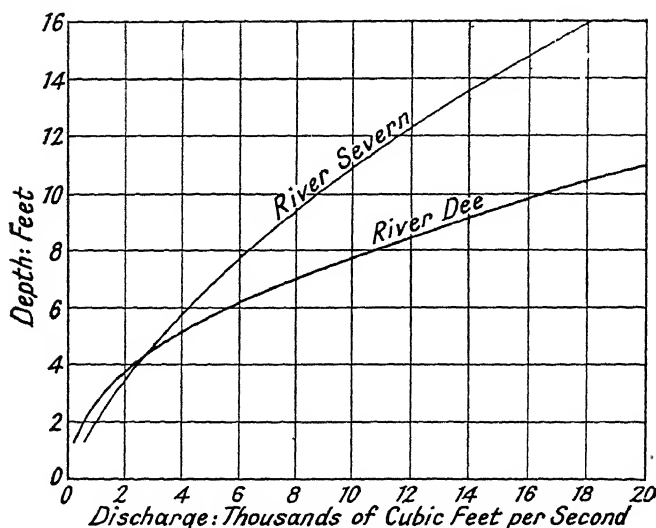


FIG. 108.—Typical stage-discharge curves.

expressed in water level, and the corresponding rate of discharge (Figs. 108, 109); if the site has been properly chosen (§ 158), then after sufficient observations have been plotted covering a wide range of levels, a smooth mean curve can be drawn between the experimental points. This is the stage-discharge curve.

The curve may thus be regarded as a means of interpolating between the various gauging observations, or it may be regarded as the calibration curve for the staff gauge at the site.

The curve will only give full value if there is a continuous record also of the water level, such as could be drawn by a recording float gauge (§ 10), or a recording pneumatic gauge (§§ 31, 33) whose construction has lately made rapid progress.⁽¹³²⁾ Then by the use of the gauge record in conjunction with the stage-discharge curve the discharge on any given date can be read off and the total flow during a period of days or weeks can be integrated.

173. Types of Stage-discharge Curve. In an ideal channel having uniform bed-slope and in which uniform flow always occurred it would be possible to plot the stage-discharge curve from the result of a single discharge observation. For the simplest case in which the water depth d is very small compared with the bed-width, and the cross-section is rectangular, the relationship would be of the form $q \propto d^{\frac{3}{2}}$.

Natural rivers never show so straightforward a correlation, although some of them approach it; as a rule each gauging site has its own characteristics—which, of course, it is the function of the stage-discharge curve to reflect—these depending on the configuration of the gauging section and on the longitudinal profile of the stream bed. Typical curves are reproduced in Fig. 108. The one for the River Severn at Bewdley⁽¹³³⁾ refers to a relatively slowly-moving stream in which the mean velocity at maximum recorded discharge hardly exceeds 5 ft./sec.; whereas the River Dee (Scotland)⁽¹³⁴⁾ runs at a mean velocity that may approach 9 ft./sec., and the surface slope continuously increases as the depth and the area increase.

To deal with such rivers as the Dee, where floods come down far too swiftly to allow a complete current meter gauging to be made at a given stage, a system has been evolved⁽¹³⁵⁾ of plotting a separate stage-discharge curve for each vertical across the section. There may just be time to make a multiple-point measurement of the mean velocity in the vertical (§ 157) before the stage alters beyond permissible limits, and then after a complete collection has been made the results can be combined into a single curve of the orthodox type.

As all stage-discharge curves express a relationship which has some kind of affinity with the basic law $q = Kd^n$, it is

often advantageous to plot them on logarithmically-divided chart paper. Departures from the ideal straight-line graph can then easily be noticed, and in any event the actual graph will rarely depart greatly from a straight line, thus rendering interpolation more accurate.

174. Validity of Stage-discharge Curves. The causes which may increase, beyond normal limits of perhaps ± 3 per

cent., the error involved in accepting information from stage-discharge curves are :

(i) Actual changes in the channel bed. These include erosion of the banks or silting of the bed from natural causes, or the erection of artificial works across the stream downstream of the gauging site. The remedy is to correct the curves frequently enough to keep pace with changing conditions.

(ii) Regulation on movable control works downstream—opening or closing of sluices, barrages, etc., diversion of water from or influx of water into the main stream—which, by the creation or modifica-

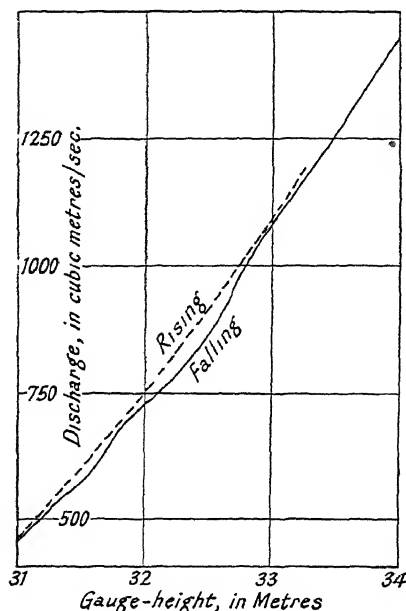


FIG. 109.—Stage-discharge curves for River Nile, above Second Cataract.

tion of backwater or drop-down curves, may cause a change of water level at the gauging site unrelated to changes in discharge.

(iii) Varying effects of rising and falling stages. When the river is rising rapidly the surface slope and therefore the discharge at the gauging site may be greater, for a given staff-gauge reading, than the corresponding slope and discharge with a falling river. This may require virtually a separate stage-discharge curve for the rising and for the falling stages, of which examples ⁽¹³⁶⁾ are given in Fig. 109.

It is to be noticed that an *existing* fixed control work, such as a weir whose backwater extends beyond a gauging site, by no means necessarily destroys the value of the site ; the stage-discharge curve may still be a stable one, even if a markedly distorted one. The real difficulty may be that at low water the velocity in the pool above the weir may be too small to be accurately measured.

CHAPTER XI

MEASUREMENT OF DISCHARGE IN OPEN STREAMS

(ii) BY WEIRS AND FLUMES

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175. Transition from Natural to Artificial Control Sections. The ultimate object of many of the measuring systems described in the preceding chapter was to calibrate a water-level gauge so that its readings could be used as a measure of discharge. There, the control section was a natural one, and all that could be done was to choose from the limited number of sites available the least irregular and unstable one. As a consequence it was impossible to foresee exactly what form the head-discharge correlation would have.

In the present chapter the measuring methods discussed all utilise an artificial control section which is intended to be of such a simple shape that the head-discharge relationship can be expressed mathematically, thus enabling the discharge to be computed from the water level without the need for calibration. In practice, though, even so elementary a control section as a rectangular one imposes such complexities on the

flow of the water that calibration is desirable in all but the most favourable conditions (§§ 206-211).

The range of devices can be classified into

- (i) Sharp-edged weirs.
- (ii) Broad-crested and round-crested weirs.
- (iii) Throated flumes.

They may either be specially built for gauging purposes, or they may be control works—dams, barrages, and the like—which can incidentally be pressed into service for flow measurement. The three classes are listed in the order in which they were developed, revealing a trend towards a type of control section which more and more resembles the original section of the natural waterway; for experience has shown that the less the flow of a natural stream is interfered with the fewer will be the troubles that accumulate about the gauging site.

Descriptions of the secondary appliances used for measuring the head or water level will be found in Chapters I and II, while flow-indicating, flow-recording, and flow-integrating apparatus is described in Chapter XIII. *See also* § 198.

SHARP-EDGED WEIRS

176. Triangular and Suppressed Rectangular Weirs.

As the construction and use of small weirs of these types suitable for indoor measurement have already been described in §§ 85-91, it is here only necessary to mention the modifications that may be required for relatively large-scale outdoor gaugings. Under such conditions triangular weirs will rarely be needed and will not be further mentioned.

For precise gaugings with suppressed rectangular weirs all the requirements specified in § 85 must be fulfilled. This means that a length of many feet of the waterway must have a horizontal bed and vertical parallel sides finished in smooth cement. The sharp-edged weir plate itself (Fig. 110) may be screwed to an angle-iron and mounted on a brick or timber bulkhead, but the entire upstream surface must be smooth and vertical. A drain-pipe through the bulkhead must not be forgotten. The best way of securing the indispensable tranquillity of flow in the rectangular approach channel is to locate the gauging station at the downstream end of a long, uniform

reach of natural channel, thus making the transition from the natural section to the rectangular section as gradual as possible. The larger the weir the more difficult it becomes to correct an initial lack of symmetry in the flow of the approaching water; moreover, in natural streams baffles are rarely permissible because they would quickly become clogged by floating refuse.

The procedure for taking the zero reading of the gauge outlined in § 86 now requires to be modified, for it would take far too long to bring the still water surface into the plane of the weir crest when the surface has an area of a dozen square yards or so. The modification is illustrated in Fig. 110; it involves the use of a temporary hook gauge which is clamped near the weir plate. With the pool water surface at rest at any convenient depth below the weir crest, the temporary

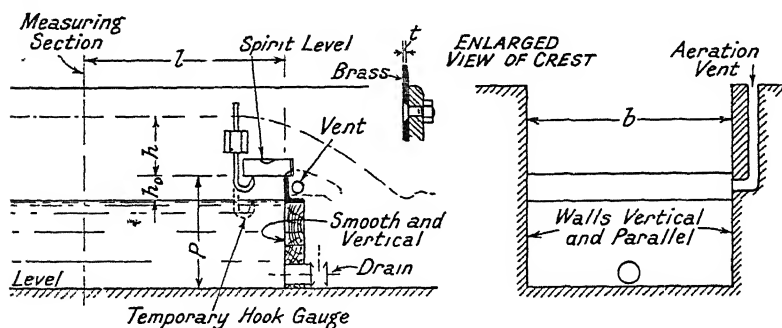


FIG. 110.—Arrangement of suppressed weir.

hook gauge and the main water-level gauge are both read; then the temporary hook gauge is adjusted with the help of a spirit level, so that its point is in the plane of the weir crest. The difference between the two readings of this gauge gives the distance h_0 , and by adding this amount to the still water reading of the main gauge the zero of this main gauge is found. The temporary gauge can then be taken away. Almost certainly the most convenient location for the main gauge will be in a gauge well, as suggested in Fig. 112. The problem of diverting or arresting the flow of the stream while the zero-setting operation is in progress may clearly be an awkward one.

177. Suppressed Weir Coefficients. Unfortunately the Rehbock formula (11), § 88, cannot be applied indiscriminately in formula (10), § 88, when computing the flow over outdoor

suppressed weirs; for it only shows the *minimum* quantity that would flow over the weir *if every possible precaution* has been taken to fulfil *quite strictly and literally* all the relevant stipulations on which the formula is based (§ 85). By exercising constant vigilance these conditions can be realised if the discharge does not exceed perhaps 2 or 3 cu. ft. per second; and even for weirs up to 4 ft. wide under a head of 2.75 ft. the discharge *can* be found to agree with the Rehbock formula if all the skill and resources of a first-class research institution ⁽¹³⁷⁾ are brought to bear on the investigations. Yet, on the other hand, experimenters of equal standing on other occasions have found ⁽¹³⁸⁾ that the actual discharge is invariably *greater* than the discharge calculated from the Rehbock formula. There has thus been developed a series of formulæ which may give slightly different values for the discharge when applied to the same experimental observations. The best-known of these are—

- (i) Bazin's formula.
- (ii) Frese's formula.
- (iii) The S.I.A. formula (developed by the Swiss Society of Engineers and Architects).
- (iv) Rehbock's formula.

It is only necessary to quote Bazin's formula here, because the zone included between Bazin's values and Rehbock's values usually includes also the other two sets of values.

If dimensions are expressed in *feet*, then according to *Bazin* the value of the coefficient of discharge to be used in formula (10), § 88, is

$$C_d = \left(0.607 + \frac{0.0148}{h}\right) \left[1 + 0.55 \left(\frac{h}{P + h}\right)^2\right] \quad (19)$$

178. Choice of Weir Formula. The comparative plottings in Fig. 111 demonstrate in rather a startling fashion how wide is the zone of uncertainty between the two limiting curves, making it imperative to find some working method, if only a crude one, for narrowing the range. Such a rule is this: the smaller the discharge, the more likely is the Rehbock formula to give correct results, and the bigger the discharge, the more likely is the Bazin formula to be right. As suggested in the

last Section, the Rehbock formula should give reasonably reliable results for discharges not exceeding 2 to 3 cu. ft./sec.; while if the discharge is over 20 cu. ft./sec. the chances are that the Bazin values will be as good as can be expected.

When we pass from the elaborately-controlled discharge observations of world-renowned investigators to routine gaugings supervised by busy engineers whose assistants have little time for incessantly nursing the gauging equipment, the fog of uncertainty deepens again. Yet here again, although there

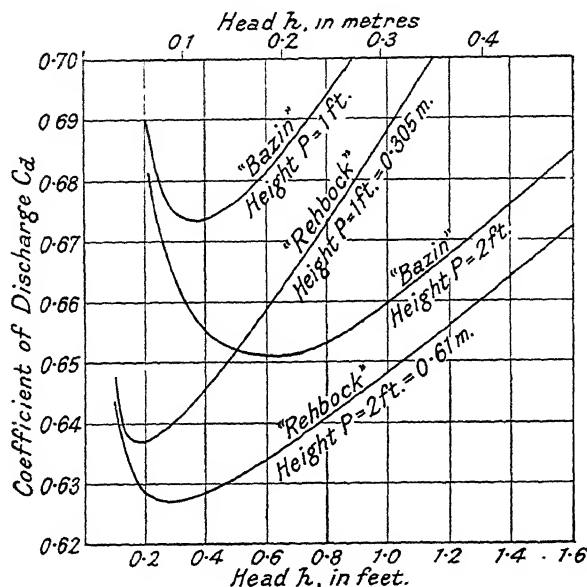


FIG. 111.—Comparison of suppressed-weir coefficients.

are no sharp unwavering rays to give guidance, visibility is slightly better in some directions than in others. We can be sure that *any* departure from the standardised conditions will invariably *increase* the discharge for a given measured head. Apart from actual gross errors in measuring the head or the weir dimensions, then, the Rehbock formula will invariably *under-estimate* the discharge if (i) the weir crest is in the slightest degree rounded instead of being dead sharp, (ii) the upstream face of the weir partition is rough or uneven instead of being smooth, (iii) the ventilating openings are too small or are

choked. or (iv) the velocity distribution in the approach channel is abnormal by reason of eddies, swirls, etc.

As average working conditions make some slight departure from the ideal requirements inevitable, this still further increases the likelihood that large discharges can be estimated more correctly by the Bazin formula than by the Rehbock formula. The opinion is gaining ground ⁽¹³⁷⁾ that possibly the range of uncertainty can be restricted by actually exploring the velocity distribution in the approach channel by means of the current meter.

Example: A suppressed rectangular weir has a width of 6.02 ft., a height of 3.51 ft., and the measured head of water is 1.89 ft. What would be the discharge?

The value of the coefficient of discharge using the Rehbock formula (11), § 88, is

$$C_d = 0.605 + \frac{1}{320 \times 1.89 - 3} + \frac{0.08 \times 1.89}{3.51} = 0.650.$$

The value using the Bazin formula (19), § 177, is

$$C_d = \left(0.607 + \frac{0.0148}{1.890} \right) \left[1 + 0.55 \left(\frac{1.89}{5.40} \right)^2 \right] = 0.656.$$

Accepting the Bazin value as being the more likely, we find from formula (10), § 88, that

$$\begin{aligned} q &= 0.656 \times \frac{2}{3} \times 6.02 \times 8.03 \times 1.89 \sqrt{1.89} \\ &= 54.8 \text{ cu. ft./sec.} \end{aligned}$$

179. Fully Contracted Rectangular Weirs. These may be used when the parallel rectangular approach channel required by the suppressed weir is impracticable. Typical conditions are shown in Fig. 112. The vertical ends as well as the sill or crest of the weir are sharp-edged, thus imposing *end contractions* as well as a *bottom contraction* on the nappe or sheet of water flowing over the weir. (The suppressed weir is so called because its end contractions are suppressed—it has no end contractions.) One small simplification that results is that there is no longer any need for ventilation holes beneath the nappe, because air has free access all round the nappe; but, on the other hand, the obscurity concerning conditions of flow in the approach channel makes precise estimation of the discharge as difficult as ever. If irregular velocity distribution had a disturbing effect on suppressed weir coefficients, it will assuredly have a no less serious effect now that the approach

channel may be the natural stream bed whose shape and proportions have no formal relation to those of the weir.

Francis formula is the one most commonly chosen for fully contracted weirs:—

$$q = 0.623 \left(b - \frac{h}{5} \right) \cdot \frac{2}{3} \sqrt{2g} [(h + h_v)^{\frac{3}{2}} - h_v^{\frac{3}{2}}] \quad (20)$$

where h_v is the *head of approach* or velocity head in the approach channel.

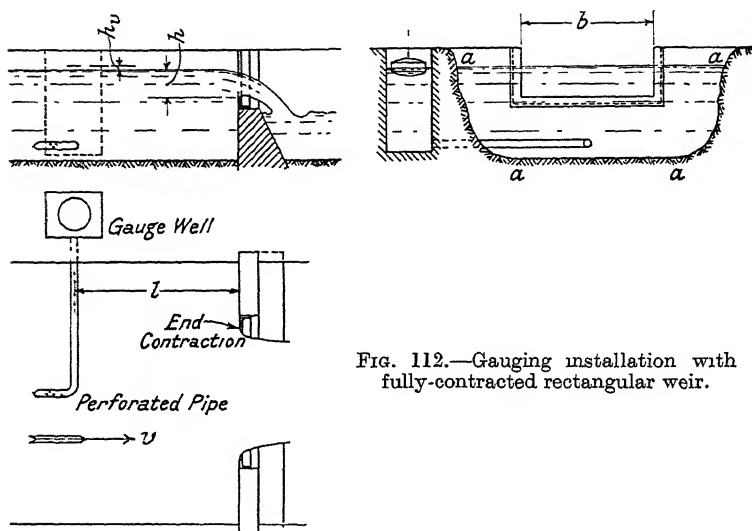


FIG. 112.—Gauging installation with fully-contracted rectangular weir.

In this formula the increasing effect of the end contractions as the head rises is manifested in a diminution of the coefficient

$$C_a = 0.623 \left(\frac{b - \frac{h}{5}}{b} \right),$$

and the influence of the velocity in the approach channel is taken care of by the term h_v . In the suppressed weir formulæ this term was not separately assessed as the general form of the expression for C_a already took it into account.

The *head of approach* h_v is evaluated by a process of successive approximation. The approximate discharge over the weir is first found by inserting in the Francis formula the

measured head h and ignoring the term h_v ; then the cross-section of the approach channel $aaaa$ at the measuring section (Fig. 112) is estimated $= A$, and the approximate velocity of approach v will then be $\frac{q}{A}$. The required value of the head of approach is now $h_v = \frac{v^2}{2g}$, and by using this together with the measured head h in the formula the true discharge is computed. Strictly speaking, a corrected value of v should next be worked out, but unless the approach velocity is very high such refinement is needless.

Example: What would be the discharge over a fully contracted rectangular weir 14.97 ft. wide working under a head of 2.41 ft., if the cross-section of the approach channel at the measuring point is 108 sq. ft.?

From formula (20) approximate provisional value of the discharge is

$$q = 0.623 \left(14.97 - \frac{2.41}{5} \right) \times \frac{2}{3} \times 8.03 \times (2.41)^{\frac{3}{2}} \\ = 180.8 \text{ cu. ft./sec.}$$

Consequently velocity of approach (first approximation)

$$= \frac{180.8}{108} = 1.67 \text{ ft./sec.,}$$

and head of approach

$$= h_v = \frac{1.67^2}{64.4} = 0.043 \text{ ft.}$$

The term $[(h + h_v)^{\frac{3}{2}} - h^{\frac{3}{2}}]$ in equation (20) thus has the value

$$[2.453^{\frac{3}{2}} - 0.043^{\frac{3}{2}}] = 3.83,$$

and the corrected value of the discharge is

$$q = 184.8 \text{ cu. ft./sec.}$$

The second approximation for the head of approach is found to be 0.046 ft., and the second approximation for the discharge q is 186.0 cu. ft./sec. This is sensibly greater than the first approximation, 184.8 cu. ft./sec., showing that in this case it was worth while to make a corrected estimate of the head of approach. But there would be no object in making still closer approximations, and the final estimate of the discharge could be given as

$$186.0 \text{ cu. ft./sec.}$$

180. Fully Contracted Weir Formulæ. Recent experiments suggest ⁽¹³⁹⁾ that for crest lengths b of 4 ft. and over, for a range of heads between 0.2 and 0.3 of the crest length b , and with artificial rectangular approach channels, the Francis formula can evaluate the discharge with an error of hardly more than 1 per cent.; but for shorter weirs the formula always *under-estimates* the discharge by an increasingly serious amount as the ratio $\frac{h}{b}$ passes outside the limits just mentioned. Remembering also the sources of error specified in § 178 that might operate also to vitiate the results of gaugings by fully contracted weirs, it is fairly safe to say that the actual discharge will *probably* always be greater than the discharge computed by the Francis formula. An additional chance of error will occur if the width of the approach channel is less than $(b + 4h)$, or if the height of the weir from the stream bed to the weir crest is less than $3h$. Reasonable overall limits of error for routine gaugings without special supervision may thus be offered as $+2$ to -4 per cent.

Exponential formula. Various alternative formulæ for fully contracted weirs have been proposed, but in view of the limited confidence that is nowadays placed in such gaugings it is only worth while to quote the *Barnes* formula ⁽¹⁴⁰⁾: it is

$$q = 3.324(h + h_v)^{1.49} b^{1.11} [b + 2(h + h_v)]^{-0.11},$$

where q is expressed in *cu. ft./sec.*, dimensions are in *feet*, and h_v is a nominal value for the head of approach $= \frac{v^2}{70}$.

This exponential form increases the labour of working out a single discharge, but it permits straight-line graphs to be plotted on logarithmically-divided charts from which the discharge can directly be read.

181. Other types of Sharp-edged Weirs. (i) *Trapezoidal weir.* This is a fully contracted weir in which the ends are not vertical but splayed out at an angle of 14° with the vertical—a batter of very nearly 1 horizontal to 4 vertical (Fig. 113 (I)). The coefficient C_d is consequently hardly affected by changes in the ratio $\frac{h}{b}$ as it is in the Francis formula for rectangular

weirs; for a range of $\frac{h}{b}$ of 0.1 to 0.4, the value of C_d may be taken as 0.632, and the resulting discharge formula will be

$$q = 0.632 \times \frac{2}{3} b \sqrt{2g} [(h + h_c)^{\frac{3}{2}} - h_c^{\frac{3}{2}}]. \quad (21)$$

For the relatively small trapezoidal or *Cippoletti* weirs that are ordinarily used, the error in estimating discharge by this formula may be taken as ± 2 per cent.⁽¹⁴¹⁾

The advantage of having a stable coefficient and therefore a true relationship $q = Kh^{\frac{3}{2}}$ is chiefly realised when the flow is to be integrated (§ 218).

(ii) *Compound weirs.* These are useful when the range of flow is very great, which might often occur in a stream or small river which is nearly dry in summer but which brings down heavy floods in the winter. In the typical compound weir shown in Fig. 113 (II) the triangular area (§ 89) will gauge the small flows accurately, while the much larger combined area is available for the upper range of discharge. Naturally the head-discharge relationship is here a wholly empirical one

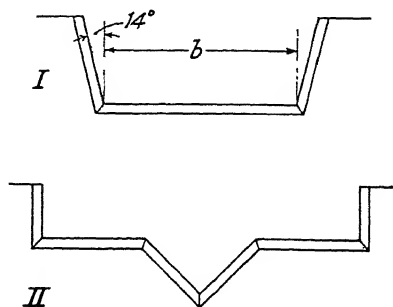


FIG. 113—Trapezoidal and compound weirs.

only to be established by calibration, and probably in any event there will be uncertainty at the transition stage when the water just begins to rise above, or just recedes from, the interrupted crest line of the rectangular part of the weir.

Another common type of compound weir is of stepped rectangular shape.

182. Limitations of Sharp-edged Weirs. Among the disabilities which have led to the partial supersession of sharp-edged weirs are—

(i) The weir must work under clear-overfall or free-discharging conditions and cannot be submerged. This means that the water level downstream of the weir must *never rise above the weir crest*. Sharp-edged weir formulæ are only valid if atmospheric air has free access to the underside of the nappe,

through special ventilation ducts if necessary, and therefore to have a margin in hand the weir crest should always be at least 2 to 3 ins. above the maximum downstream level.

(ii) The sharpness of the crest cannot be maintained indefinitely. In a natural river there are bound to be floating solids—logs, branches, and the like—which will make indentations as they pass over the crest, resulting in an altered weir coefficient.

(iii) The weir is excessively sensitive to flow conditions in the approach channel.

(iv) The pool upstream of the weir forms an excellent settling tank. Sand, stones, and gravel carried along by natural rivers are bound to be deposited here, sometimes in such quantities that in time the pool may be filled up solid as high as the weir crest. Although these deposits may periodically be cleared out, the weir performance in the meantime is probably so seriously affected that the gaugings have hardly more than a nominal value.

BROAD-CRESTED AND ROUND-CRESTED WEIRS

183. Broad-crested Weirs. A broad-crested weir may be regarded as a flat-topped wall built across the channel having a thickness l_1 (Fig. 114 (I)), the upstream edge being preferably rounded. In flowing over this horizontal broad crest the water is assumed to be drawn down to the critical depth; the thickness of the sheet is then $\frac{2}{3}h$ and the ideal uniform velocity throughout is $\sqrt{2g \cdot \frac{h}{3}}$. It follows that the general discharge formula is

$$q = C_d \times 0.385b\sqrt{2g}(h + h_v)^{\frac{3}{2}} \quad (22)$$

where b , as before, represents the transverse crest length, C_d is the coefficient of discharge, and h_v is the velocity head in the approach channel, or head of approach, which must be estimated by successive approximation (§ 179).

In spite of the many experiments that have been made to find the precise shape of weir that will have a stable value for the coefficient C_d as the head varies, there seems to be no record of any wholly successful ones. Weirs with truly horizontal crests as at (I), Fig. 114, are certainly disappointing, for if the thickness of the crest l_1 is too long the sheet of water

flowing over it will break up into waves, and if it is too short the coefficient will sensibly increase as the depth increases.⁽¹⁴²⁾ The most promising and consistent results are given by weirs having a slightly sloping crest, as at (II), and of course a rounded upstream edge.⁽¹⁴³⁾ If the slope in a downstream direction is about 1 in 20 to 1 in 40, with a length l_1 of about three times the maximum head, it seems likely that the coefficient will vary from perhaps 1.00 under a head of 0.5 ft. to 0.97 under a head of 1.5 ft. There is no evidence that the upstream slope (as shown by the broken line in the diagram) has an appreciable effect on the coefficient, or that within due limits irregular

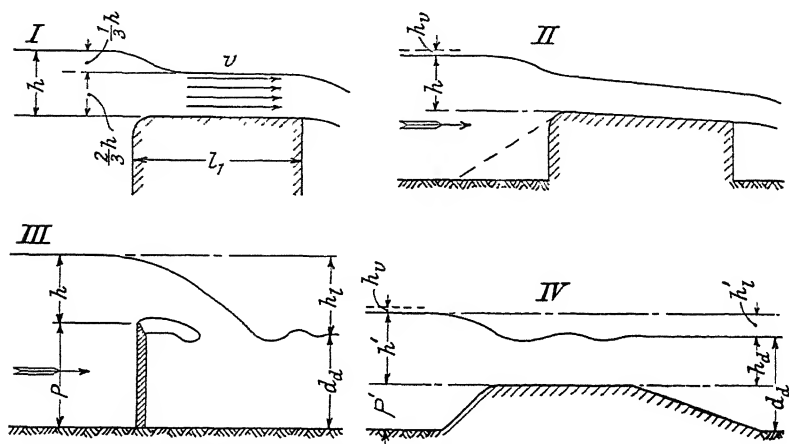


FIG. 114.—Broad-crested weirs compared with sharp-edged weir.

velocity distributions in the approach channel need be studied. Nevertheless, it would be unwise to predict the performance of an uncalibrated broad-crested weir within closer limits than ± 4 per cent.

184. Submerged Broad-crested Weirs. One of the chief advantages of the broad-crested weir is that it can be submerged quite considerably without suffering any change in its characteristics; that is to say, it will still behave as a free-discharging weir and formula (22) will still be applicable. Even under the most unfavourable conditions, with a vertical drop at the downstream end as in Fig. 114 (I) and (II), the downstream head over the weir may be 0.66 of the upstream

head, while with a more suitable shape of weir substantially greater submergences are possible.

Comparison with a sharp-edged rectangular weir shows what great practical importance this property has. Suppose that under maximum flow conditions the natural depth in the stream is d_a , Fig. 114 (III) and (IV). Now to avoid submergence the height P of the sharp-edged weir must be materially greater than d_a (§ 182 (i)), and the resulting afflux will be h_i . The only stipulation limiting the height of the broad-crested weir is that the downstream head h_a must not exceed $0.66 (h' + h_v)$, and this can be fulfilled by building the weir of height P' only, so heading up the water by the small amount h_i .

Example: The maximum discharge of a stream is estimated to be 2.5 cu m/sec, and the corresponding water depth is 1.0 m. Compare the afflux produced by (a) a sharp-edged suppressed rectangular weir, and (b) a broad-crested weir, assuming that they both have a crest length b of 2.0 m.

Adopting provisionally a suppressed weir coefficient C_d of 0.66, we find from formula (10), § 88, that the necessary head over the rectangular weir is about 0.74 m.; and since the height P must be greater than 1.0 m., say 1.1 m., the afflux will be about $1.1 + 0.74 - 1.0 = 0.84$ m.

For the broad-crested weir a coefficient C_d of 0.98 may be taken. By inserting this value in formula (22), § 183, the corresponding head is about 0.82 m. But since the weir crest may be set an amount $0.66 \times 0.82 = 0.54$ m. below the downstream water-surface, the afflux is only about 0.28 m., or just one-third of the suppressed weir afflux. Actually it might even be less, for the figure 0.82 m. includes also the velocity head which may easily amount to 0.03 m.

It is interesting to note that under comparable conditions the head over the weir crest is greater for the broad-crested weir than it is for the sharp-edged weir.

In streams flowing through flat country the small afflux h'_i (Fig. 114) would probably be unobjectionable, while the afflux h_i demanded by the sharp-edged weir might rule out this type entirely. Moreover, the pool velocity or velocity of approach upstream of the broad-crested weir would be materially higher than in the pool of the sharp-edged weir, thus lessening the prospect of silting up; and in any event a considerable quantity of deposits would be needed to spoil the broad-crested weir performance.

On account of their sloping downstream *glacis*, control weirs built across rivers and calibrated for measuring purposes may be even less susceptible to submergence than simple broad-crested weirs. The weir across the Rosetta branch of the Nile at the Delta Barrage is one of these; ⁽¹⁴⁴⁾ it is 420 m. long, 3 m. high, 3 m. wide at the horizontal crest, with an upstream slope of 1:3 and a downstream slope of 1:12 continuing down to the river bed. So long as the upstream head does not exceed 1.78 m. the true relationship $q = Kh^3$ is maintained, although by that time the downstream head h_a has risen to 1.63 m., representing a submergence of 92 per cent. Weirs with this characteristic are often termed *standing-wave* weirs.

185. Round-crested Weirs. These are rarely built expressly for measuring purposes, but they must often be adapted

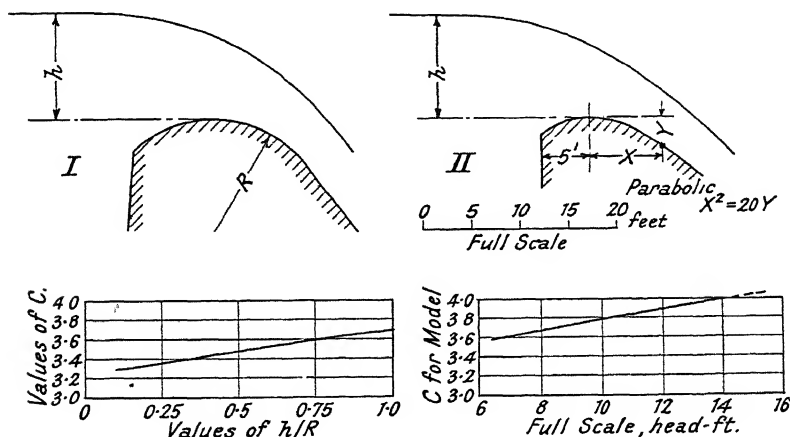


FIG. 115.—Weirs with cylindrical and parabolic crests.

for flow measurement, because the overflow spillways of dams and barrages may be of this form. The cross-section of the crest is sometimes circular, of radius R (Fig. 115 (I)), and sometimes parabolic (II); the advantage of the latter is that the minimum possible head is required to spill a given discharge over a given length of crest.

The flow over such weirs is usually expressed by the formula

$$q = Cbh^{\frac{3}{2}} \quad (23)$$

where C is not a true coefficient of discharge but is an empirical coefficient which depends principally on the ratio h/R . The values given below for use in this equation only hold good when h and b are expressed in *feet* and q in *cu. ft./sec.*

All experimenters find that for *circular* or cylindrical-crested weirs the coefficient invariably increases as the head increases. The values plotted in Fig. 115 (I) refer to the spillway whose section is shown to scale; it is that of a model of the Madden Dam, Panama.⁽¹⁴⁵⁾ They agree reasonably well with the results of tests ⁽¹⁴⁶⁾ on a model of the Treig Dam (Scotland); this dam has upstream and downstream slopes of 1:3 and the value of C increases from 3.13 when $\frac{h}{R}$ is 0.10 to 3.24 when $\frac{h}{R}$ is 0.27.

A mathematical expression for the coefficient C has been proposed by Prof. J. J. Doland; ⁽¹⁴⁷⁾ it is $C = K\left(\frac{h}{R}\right)^n$, where the factor K may vary from 3.75 to 3.32 according to the details of construction of the weir, and the exponent n varies correspondingly from 0.10 to 0.16. The term h is intended to be corrected by the addition of the head of approach h_a .

Prof. Rehbock has deduced a formula for circular-cylindrical weirs analogous to his sharp-crested weir formula (11), § 88. The *coefficient of discharge* C_d for the round-crested weir is computed from the formula

$$C_d = 0.312 + \sqrt{0.30 - 0.01\left(5 - \frac{h}{R}\right)^2} + 0.09\frac{h}{P},$$

and its value is inserted in formula (10), § 88. It will be noticed that this formula includes a term which takes account of the head of approach, just as the sharp-crested formula (11) does. Experiments at Munich ⁽¹⁴⁸⁾ have shown that this modified Rehbock formula is only acceptable for weirs having an upstream vertical slope and a downstream slope of 3 to 2 ($56\frac{1}{2}^\circ$ with the horizontal); and they show, moreover, that any given round-crested weir under a given head is subject to inexplicable variations in discharge. Until these questions are cleared up the limits of error in estimating the discharge over an uncalibrated round-crested weir cannot justifiably be reduced to less than ± 4 per cent.

186. Parabolic Weirs. The basis on which these are usually designed is that when discharging under the normal head h_0 , the shape of the downstream part of the crest should correspond as nearly as possible with the shape of the underside of the nappe of an equivalent clear-overfall sharp-edged rectangular weir discharging under a head of $1.12 h_0$. A parabolic profile fulfils this condition sufficiently well if the equation of the parabola is $X^2 = (1.8 h_0)Y$, where the co-ordinates X and Y in feet are measured from the highest point of the crest, as in Fig. 115 (II). The minimum radius R at the origin of the parabola will then be $R = 0.9 h_0$, and by inserting this value in the formulæ for circular-crested weirs quoted in § 185, these formulæ will give useful guidance about the performance of parabolic weirs also. In formula (23), for example, it has been suggested ⁽¹⁴⁹⁾ that the coefficient C should have the value $C = 3.97 \left(\frac{h}{h_0} \right)^{0.12}$, where h_0 is the head that satisfies the equation $X^2 = (1.8 h_0)Y$, and h is the actual head over the weir. The crest shown to scale in Fig. 115 (II) is that of the Keokuk Dam (Mississippi), and the graph below it gives the results of classic experiments, ⁽¹⁵⁰⁾ both under the full-scale head of 11 ft. and on models. As the minimum crest radius is here 10 ft. it can be seen that the relation between C and $\frac{h}{R}$ agrees fairly well with the values obtained from the circular-crested weir (I). The experiments clearly proved the effect of interference resulting from the piers 6 ft. thick that separated the spillways 30 ft. long (§ 200). In experiments on other dams ⁽¹⁵¹⁾ this factor has been taken into account by modifying formula (23) thus,

$$q = C(b - kNh)h^{\frac{3}{2}},$$

where b is the overall length of the spillway, N is the number of piers, and k is a factor having a value of about 0.04 which depends on the shape of the piers.

It is evident from the types of exponential expression for C that have been put forward for round-crested weirs that the relation between q and h can be put in the form $q = Kh^n$, where the exponent n will have a value of about 1.62. Thus if q is plotted against h on logarithmic paper the resulting graph will probably be a straight line.

THROATED FLUMES

187. Classification of Flumes. Because flumes have only recently been adapted for hydraulic measurements, and because progress in their design has been made in such widely scattered regions—India, Great Britain, and America—the terms used to describe these devices are not yet standardised. But the connection between flumes and weirs is definite enough: measuring flumes are a development of the broad-crested weir intended to realise in a still higher degree the advantages of (i) independence of the precise shape of the weir crest, (ii) ability to work submerged, and (iii) minimum disturbance of the natural flow of the stream and therefore relative immunity from impaired performance due to silting.

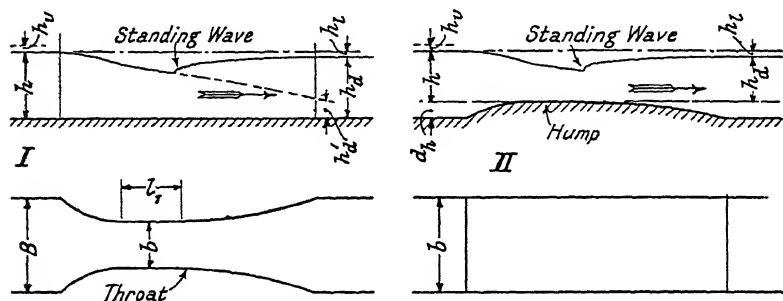


FIG. 116.—Standing-wave flumes.

Comparing the flume sketched in Fig. 116 (I) with the two weirs in Fig. 114 (III) and (IV) it is seen that the weir height has shrunk from P in the sharp-edged weir to P' in the broad-crested weir and has vanished altogether in the flume; the flume has a level flat floor and side contractions only. In other types of flume, as in Fig. 116 (II), there remains a sort of vestigial weir which is now called a *Hump* having a height d_h , the side walls being parallel; while still another design has both side contractions and a hump (Fig. 117). They all have in common with the broad-crested weir the characteristic flow equation (22), § 183, the discharge being *wholly independent* of the downstream head so long as this does not exceed the appropriate limit for each particular design. In the flat-floor flume (I), for instance (Fig. 116), through which a steady

discharge is assumed to be flowing, the downstream head or submergence could change from h_a to h'_a (as a result of regulation still further downstream) without producing the slightest effect on the upstream or operating head h .

Even when the limit of submergence has been overstepped the flume may still be used for gauging purposes by making depth observations both at the upstream measuring section and at the throat, and inserting these values in an equation identical with that developed for constriction meters.

In this book the term *standing-wave flume* will be used to distinguish all free-discharging devices which depend on a single upstream head measurement only, the justification being that it is only the standing wave formed in or near the throat that endows the flume with its greatly valued high submergence ratio $\frac{h_a}{h}$. The term *Venturi flume* will be applied solely to devices in which both an upstream and a throat depth measurement are required, § 196. It must be made clear that this is a purely arbitrary distinction that is in no way universally recognised.

188. Rectangular Standing-wave Flumes. In flumes having a rectangular cross-section both in the channel and in the throat, it appears ⁽¹⁵²⁾ that the length l_1 of the throat in relation to the width b has a predominating influence on the stability of the coefficient of discharge C_d ; the greater the ratio $\frac{l_1}{b}$, within reasonable limits, the more uniform C_d becomes under variations of discharge. Comparing two flumes, both having a channel width B (Fig. 116 (I)) of 1.0 ft. and a throat width b of 0.394 ft., the one with a throat only 0.42 ft. long gave values of C_d ranging from 1.035 to 0.985 as the head h fell from 1.1 ft. to 0.3 ft., whereas when the throat length was increased to 1.66 ft. the extreme range of the coefficient under a similar range of discharge was 0.996 to 0.976. The effect of the *width* of the channel is stated ⁽¹⁵³⁾ to be to increase the average value of C_d from about 0.97 when B is 1 ft. to 0.99 when B is 10 ft.

With the types of waterway now being considered, of rectangular cross-section both at the upstream measuring point

and in the throat, calculation may be simplified ⁽¹⁵⁴⁾ by using a modified form of the basic equation (22), § 183. It is

$$q = C_a \cdot K \cdot 0.385b\sqrt{2g(h^3)} \quad . \quad . \quad (24)$$

where K is a factor analogous to the velocity of approach factor C_{va} , § 113, its value depending on the proportions of the waterway in the following manner:—

Value of $\frac{bh}{B(h + d_h)}$	0.1	0.2	0.4	0.6	0.8
Value of K . . .	1.003	1.009	1.038	1.098	1.219

There is thus no need for the process of successive approximation in evaluating h_v that was described in § 179, as this term does not appear in the equation at all.

It is worth noting that when the flume has a flat floor, so that $d_h = 0$, then for a given flume the value of K is invariable for all discharges; e.g. if $\frac{b}{B} = 0.5$, then $K = 1.045$. It should also be remembered that since formulæ (22) and (24) give precisely the same result, the same value of the coefficient of discharge C_a should be used in either.

The downstream flared part of the flume has no effect on the head-discharge relationship, but it materially helps to secure a high *ratio of submergence* or *modular limit*. Although this value $\frac{h_a}{h}$ may sometimes be as much as 0.92, it is prudent not to rely on a higher value than 0.7. Sometimes the modular limit may be different when the discharge is falling from what it is with a rising discharge.

189. Rectangular Flumes for Canal Gauging. The necessity that often arises for the hump (Fig. 116 (II)) can be illustrated by considering the special problems involved in designing flumes for irrigation canals. Here there are two depth-discharge relationships to be reconciled: (i) the normal stage-discharge curve (§ 173) for the downstream reach of the canal, which will generally *remain unaltered* by the building

of the flume, and (ii) the head-discharge correlation for the flume itself. Unless these are compared throughout the whole specified range of discharge there will be a possibility that although at full flow the permissible modular limit $\frac{h_d}{h}$ is not exceeded, yet at part flow the characteristics of the downstream channel may have caused its level to sink so slowly that the flume is "drowned" and its own characteristics are destroyed. Along the upstream reach there is an equally great need to keep the canal regime undisturbed, because in the conditions here envisaged the flow is critical as regards silt transport, and any change in the regime may throw down silt or alternatively promote bed erosion.

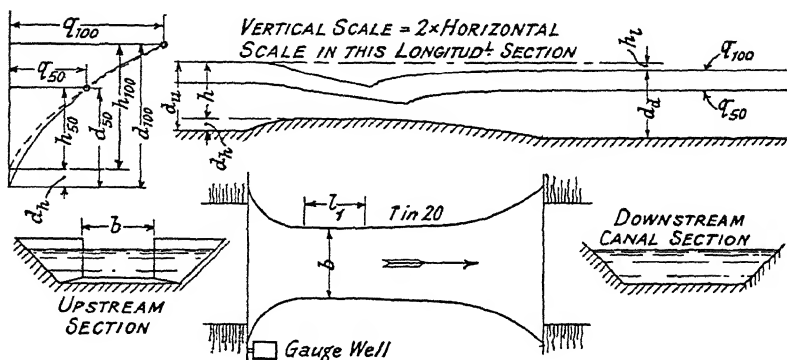


FIG. 117.—Design of standing-wave flume for canal gauging.

Referring now to Fig. 117, it will be seen how the superposition of the two discharge curves helps to fix the height d_h of the hump. The conditions here are that there shall be approximate agreement between the curves between the limits q_{100} (100 per cent. of full flow) and q_{50} (50 per cent. of full flow), the subscripts ₁₀₀ and ₅₀ for the other symbols having the corresponding significance. The continuous curve is the canal stage-discharge curve which depends upon the canal depth d , while the broken curve represents the flume head-discharge relationship depending on the head h . By suitably choosing the width of the flume b the flume curve can be expanded or contracted in a vertical direction until it fits the canal curve at

the two points q_{100} and q_{50} , and in this way the requisite height of hump d_h can be scaled off.

190. Canal Flumes (continued). So far the procedure has reached the point of ensuring *proportionality*, viz. of ensuring that the flume will impose variations of water level which nearly agree with the natural variations in the upstream reach of the canal. To safeguard against drowning it would ideally be possible to lower the floor of the downstream canal by a suitable amount, which could be found by noting what vertical displacement of the canal curve, in relation to the flume curve, would preserve the stipulated modular limit throughout the desired range. Actually this is rarely convenient, and the same result is achieved by making the hump a little higher—a course that only interferes to a negligible degree with the upstream regime.⁽¹⁵⁵⁾ Depending upon the characteristics of the canal, it is found ⁽¹⁵³⁾ that the height d_h of the hump may range from $0.1 h$ to $0.2 h$.

When d_h and b are finally fixed, the design of the flume can be continued. Fig. 117 shows the proportions of a flume to discharge 1290 cu. ft./sec. under a head of 8 ft.; ⁽¹⁵³⁾ here the throat width was made 19 ft., and the downstream flare was arranged to give the utmost possible submergence—in this case 90 per cent. It is to be noted that even if minimum overall head loss in the flume is not important, flaring may be essential to protect the bed of the downstream channel. In Fig. 117 the longitudinal section includes the water surface profiles for full-discharge and for half-discharge.

A properly-flared flume will still not give the desired recovery of head, and thus the expected high modular ratio, if the proportions of the throat are defective. As already stated (§ 188) there should be a minimum length of throat—say $l_1 = 2(h + h_v)$ —if a stable coefficient C_d is wanted, and in addition the width b must not be more than $2(h + h_v)$ or at the most $3(h + h_v)$. Should this be impracticable, then two flumes must be disposed in parallel.

191. Standing-wave Flume Calculations.

Example (i): Estimate the discharge through a standing-wave flume built in a rectangular channel 3.02 ft. wide, if the throat width is 1.30 ft., the height of the hump is 0.5 ft., and the effective head above the hump, measured at the upstream section, is 1.86 ft.

Here the value of $\frac{bh}{B(h+d_h)}$ is $\frac{1.30 \times 1.86}{3.02 \times 2.36} = 0.34$, and the corresponding value of K from the Table in § 188 is 1.028. Assuming a value of C_d of 0.98, and inserting in formula (24), § 188, we find

$$q = 0.98 \times 1.028 \times 0.385 \times 1.30 \times 8.03 \times 1.86\sqrt{1.86} \\ = 10.2 \text{ cu. ft./sec.}$$

Example (ii): When flowing under its natural regime a stream has a depth of 1 ft. when the discharge is 12 cu. ft./sec. and a depth of 4 ft. when the discharge is 140 cu. ft./sec. What would be suitable dimensions for a rectangular standing-wave flume to gauge the flow within these limits?

For a first trial, we may assume that at minimum discharge, b = throat width = $3h$, and that $C_d = 0.98$. Velocity of approach will be neglected. Inserting values in formula (22), § 183, we have (for minimum discharge conditions)

$$12 = 0.98 \times 0.385 \times 3h \times 8.03 \times h^{\frac{5}{2}},$$

from which $h^{\frac{5}{2}} = 1.32$, and $h = 1.12$ ft. The corresponding throat width is thus 3.36 ft.

Now we must find what head this throat will produce at full discharge. Inserting therefore $q = 140$ and $b = 3.36$ in formula (22), we obtain $h = 5.7$ ft. This is a reasonable value, but the heading-up would be a little excessive. Let us therefore try $b = 4$ ft. This gives a head of 0.99 ft. at minimum discharge, and a head of 5.1 ft. at maximum discharge. A hump will thus be necessary to prevent drowning of the flume at minimum flow. If the height of the hump is 0.3 ft., then at minimum flow the downstream head h_d will be 0.7 ft., and the submergence ratio will be $\frac{0.7}{0.99}$, which is a permissible value. At maximum flow the

submergence ratio will be $\frac{3.7}{5.1}$, which is likewise permissible.

The throat width of 4.0 ft. may therefore be accepted, even though it is rather wider than might be desired at minimum flow. As the average channel width would probably be 8 ft. or so, the general proportions of the flume appear to be satisfactory. The throat length might be 8 or 10 ft., and the overall length of the flume about 30 ft.

When finally constructing the discharge curve for the flume it would naturally be necessary to apply the velocity of approach correction.

192. **Trapezoidal and Compound Flumes.** Although the change from a rectangular to a trapezoidal control section in a flume destroys the simplicity of the relationship⁽¹⁵⁶⁾ between q and h , there are compensating practical advantages. The modified shape may permit the flume to conform still more closely to the natural cross-section of the stream, and the modified flow characteristics may be more appropriate for gauging very variable flows. Examples of the trapezoidal standing-wave flumes constructed by the Derwent Valley Water Board (England) are illustrated in Fig. 118. The

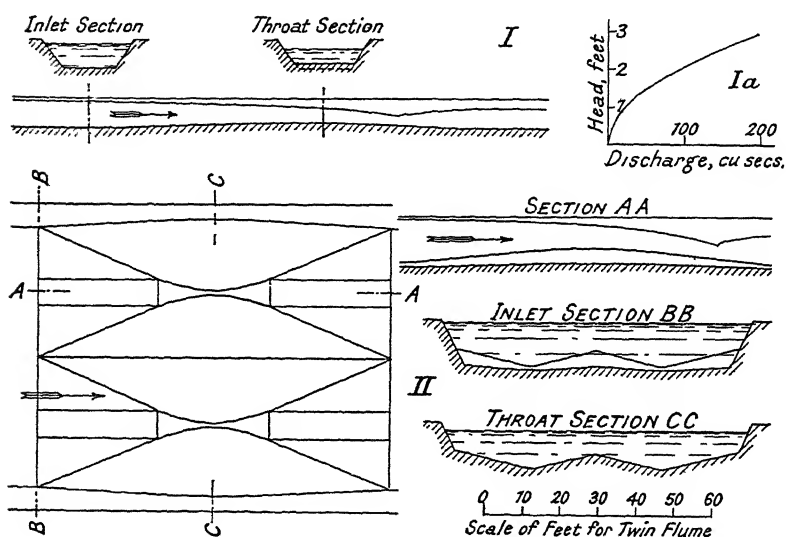


FIG. 118.—(I). Trapezoidal flume.

(II) Twin compound, trapezoidal flume

smaller single flume (I) is interposed in a concrete-lined water-course of trapezoidal section⁽¹⁵⁷⁾ having a bed-width of 9 ft. and a longitudinal slope of 1 in 1900; it has no side contractions but a low and very long (40 ft.) hump. This gradual transition from the inlet to the throat section confers nearly ideal conditions on the flow at the throat and materially assists in the calibration of the flume (§ 208). The discharge curve is reproduced in Fig. 118 (Ia); the flume has a modular limit of 0.83.

Details of the larger flume (Fig. 118 (II)) have kindly been communicated by the designer, Mr. R. W. S. Thompson,

M Inst.C.E. The flume, which measures the flow of the River Derwent, is of unusual interest, for it very nearly represents finality in respect of similarity between natural and artificial control sections; and, moreover, it was built to replace existing sharp-edged weirs which had become unserviceable due to heavy silting. The structure may be described as a twin compound flume; "twin," for the reasons explained in § 190, and "compound," in order to gauge small flows very accurately (§ 181 (ii)). The resulting variation in the head-discharge relationship at various stages of the river is shown by the following figures:—

Head in feet	2	4	6	8	10
Discharge in cu. ft./sec. .	125	710	2050	3960	6320

Value of n in expression $q = kh^n$:—

Between $h = 2$ ft. and $h = 4$ ft., $n = 2.38$

„ „ $= 8$ ft. „ „ $= 10$ „ „ $= 2.0$

These figures prove that when, during the low stage of the river, the throat cross-section resembles two triangular weirs in parallel, the performance of the flume likewise approximates to that of a triangular weir. To define the gauging section and to prevent erosion of the concrete, stainless-steel sheathing is used to protect all the areas in the throat exposed to high velocities.⁽¹⁵⁸⁾

Other types of trapezoidal flume are shown in Fig. 119.

193. Flumes for Measuring Sewage Flow. Properly designed standing-wave flumes are peculiarly well adapted for gauging the flow in main sewers, where the deposition of solids is highly unwelcome. Desirable features are indicated in Fig. 119 (I), which shows one of numerous measuring flumes at the works of the West Middlesex (London) Drainage Scheme; ⁽¹⁵⁹⁾ the invert is horizontal and semi-circular throughout, the necessary contraction being contrived by progressively reducing the radius. Here also a rustless iron throat section positively defines the area for flow, and a slit instead of a hole (which might get choked) conducts the liquid to the float well.

Variants that have been proposed for adapting existing

circular sewers for gauging purposes are sketched at (II) and (III). The first of these ⁽¹⁶⁰⁾ has a hump only, while the second ⁽¹⁶¹⁾ is of trapezoidal section. Both are formed of concrete, either cast *in situ* or, to avoid interrupting the flow, pre-cast and lowered down the manhole.

To meet special conditions in the Poona (India) Drainage Outfall Sewer ⁽¹⁶²⁾ the compound trapezoidal flume shown in Fig. 119 (IV) was designed. For flows up to 9 cu. ft./sec. the discharge formula was $q = 0.588h^{2.26}$, and for flows between 9 and 40 cu. ft./sec. the formula was $q = 0.074 h^{3.96}$ (foot units).

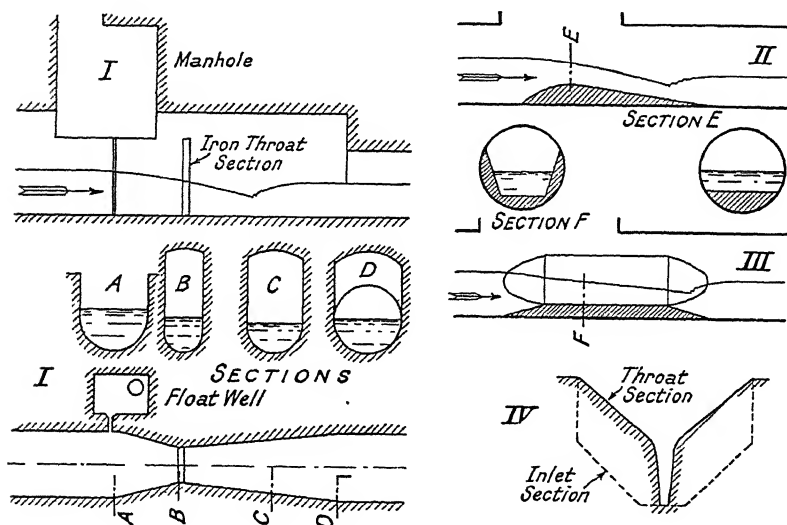


FIG. 119.—Standing-wave flumes for measuring sewage flow.

194. The Parshall Flume. Developed by Mr. R. L. Parshall, this type of standing-wave flume is now accepted in the western states of North America as a practical and reliable means of gauging, 2500 of them being in use in Colorado alone. ⁽¹⁶³⁾ It has no hump, but the floor of the throat slopes downstream in the form of a *glacis*, and the diverging part of the flume has a slight upward slope (Fig. 120). The necessary standing wave is thus encouraged to form, and so enables a modular limit of 70 per cent. to be reached. Because of the empirical rules which govern the proportions of the flume, and because, as the diagram shows, the head is measured in the

converging part of the waterway, the broad-crested weir formula (22), § 183, in its ordinary form cannot be applied. Instead ⁽¹⁶⁴⁾ the formulæ

$$\left. \begin{aligned} q &= 4bh^{1.522b^{0.026}} \\ q &= 3.75bh^{1.6} \end{aligned} \right\} \text{foot units}$$

are used, the former apparently for relatively small discharges up to 60 cu. ft./sec. and the latter for flumes 40 ft. wide discharging up to 1500 cu. ft./sec.

195. Critical-depth

Flumes. The theory underlying the design of broad-crested weirs and standing-wave flumes is that at the crest or the throat the water is drawn down to the critical depth. If this theory could in fact be realised, flow measurement would be greatly

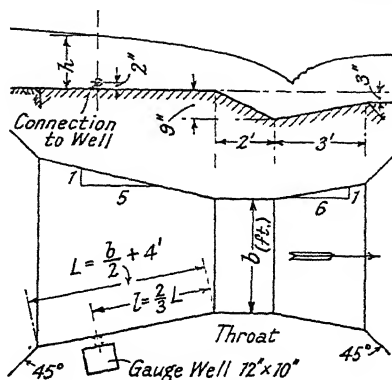


FIG. 120.—The Parshall flume.

simplified, because there exists a quite definite relationship between the critical depth and the discharge which would permit the discharge to be computed from a measurement of the throat depth alone. Upstream conditions, which in other gauging devices exercise so potent and incalculable an influence, could then be completely disregarded. But repeated attempts have failed to develop a wholly satisfactory critical-depth flume, one difficulty among many being that the point along the length of the axis at which the water falls to the critical depth is apt to move up or downstream as the discharge changes.

The reason why designers have persisted in spite of such discouragements in trying to perfect flumes of this type is that they offer almost the only means of gauging mountain torrents heavily charged with sand, gravel, and boulders. At high velocities the Parshall flume (§ 194) deals successfully with these severe duties, but at low flows there is a tendency for deposits of sand and gravel on the approach floor to disturb the calibration. A promising type of critical-depth

flume, described as the San Dinas flume,⁽¹⁶⁵⁾ has a narrow parallel throat with a gently-sloping floor (Fig. 121). The gauging section is deliberately chosen downstream of the point at which the water at maximum discharge attains the critical depth, and it was found that the measured depth at this section was related to the discharge by the formula $q = kh^n$, where the values of k and n varied with the width b as follows :—

b	k	n
1	6.35	1.321
2	13.05	1.277
3	19.90	1.245

(foot units)

These values held good for a range of head from 0.2 ft. to 2.0 ft., for discharges up to 50 cu. ft./sec., and for bed-loads of sand,

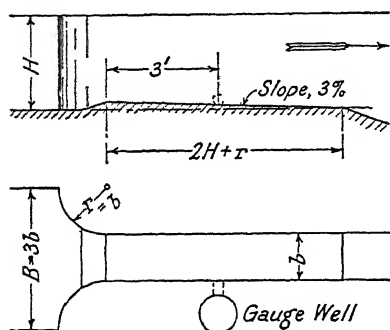


FIG. 121 —Critical-depth flume.

gravel, and boulders up to 10 ins. diameter, totalling 10 per cent. of the flow.

Great accuracy here is hardly to be looked for, but it is certainly more likely to be approached when measurements are made in the throat, where the water has had some semblance of orderly motion impressed on it, than when depth measurements are attempted in

the violently turbulent water upstream.

196. The Venturi Flume. Using the terms in the special sense that was defined in § 187, a standing-wave flume becomes a Venturi flume when the modular limit has been exceeded, when the standing wave has broken down, and when in consequence the depth in the throat is greater than the critical depth. For a given rate of discharge the upstream depth is now no longer independent of the downstream depth and therefore this upstream depth alone no longer serves as a criterion of the flow. In any event, the fact that the throat depth is greater than the critical depth takes away all justification for the use of the broad-crested weir formula (22), which must now finally be abandoned. (It should again be noted that since the same

apparatus may, and often does, serve both as a standing-wave flume and as a Venturi flume, many writers use the term Venturi flume ⁽¹⁶⁶⁾ to cover all types of throated flume.)

Nevertheless, the apparatus can still be used as a gauging device, though with lessened confidence, by measuring the head both at the upstream section and at the throat (Fig. 122) and inserting the values in a formula of the type used for constriction meters (§ 113). The symbols there used have the same general significance as those shown in Fig. 122, except that what was the measuring head h in the constriction meter is now the drop in surface level $h_0 = h - h_1$.

For the Venturi flume, then, these formulæ still hold good, viz.,

$$q = C_d \cdot a \sqrt{2g(h - h_1)} \cdot \sqrt{\frac{1}{1 - m^2}} \quad . \quad . \quad (25)$$

and
$$C = C_d \sqrt{\frac{1}{1 - m^2}},$$

where q = discharge,

B = width of (assumed rectangular) inlet section,

b = " " " " " " throat section,

h = measured head at inlet section,

h_1 = " " " " " " throat section,

A = area of inlet section = $B(h + d_h)$, where d_h = height of hump, if any,

a = area of throat section = bh_1 ,

m = area ratio = $\frac{a}{A}$,

C_d = coefficient of discharge,

C = constriction coefficient.

197. Venturi Flume Performance. The prospects of accuracy can quite fairly be assessed by comparing the hydraulic gradient of the constriction meter (Fig. 75) with the water surface of the Venturi flume (Fig. 122); it will be seen that allowing for the difference in scale they have the same general shape, as indeed they ought to have. We note in the first place that the differential head h in Fig. 75 may be anything from about 0.5 ft. to 10 or 20 ft. of water, and that it can be measured with very little risk of sensible error. On the other hand, the equivalent dimension h_0 in Fig. 122 must

always be less than one-third of the upstream depth h , and will rarely be more than a few inches or a foot. There is, moreover, grave uncertainty about the head in the throat h_1 , for a piezometric measurement will only be valid if the flow at the measuring section is truly horizontal and parallel with the bed (§ 43 (v)). And how are we to be sure of that? Finally, the velocity of approach factor has an unalterable value for a given constriction meter, whereas its value for the Venturi flume is at the mercy of every change in discharge or downstream level.

That these dubious expectations have been justified is proved clearly enough by the experimental values for C_a and C that have been published; ⁽¹⁶⁷⁾ for a single flume and a

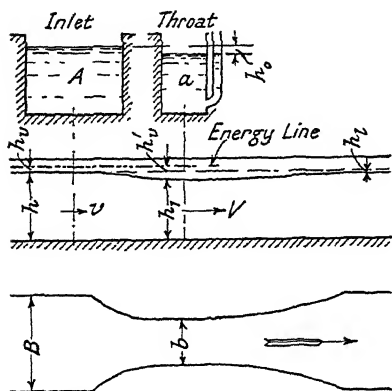


FIG. 122.—Venturi flume.

single upstream depth, the effect of increasing the discharge in a 3 : 1 ratio (by reducing the downstream depth) may be to increase the value of C_a from 0.95 to 1.02, while under less favourable conditions, reducing the discharge by one-half may increase the constriction coefficient C from 1.07 to 1.19.

On the other hand, the overall head loss h_L (Fig. 122) may amount to only 7 or 8 per cent. of the upstream head h . This is the one undoubted advantage of the Venturi flume—it imposes the lowest loss of head of any apparatus in the weir or flume category; and for this reason alone engineers are glad to instal it when nothing else will serve, and they welcome the useful information it is capable of giving when designed by specialists and when intelligently handled.

Example: What would be the discharge through the throated flume specified in *Example* (i), § 191, if the upstream head were still 1.86 ft., but the measured head in the throat were now 1.63 ft.?

The values to be inserted in formula (25), § 196, are

$$h = 1.86 \text{ ft.}$$

$$h_1 = 1.63 \text{ ft.}$$

$$A = 3.02 \times 2.36 = 7.12 \text{ sq. ft.}$$

$$a = 1.30 \times 1.63 = 2.12 \text{ sq. ft.}$$

$$m = \frac{a}{A} = 0.298.$$

$$C_{va} = \sqrt{\frac{1}{1 - m^2}} = 1.05.$$

Assuming $C_a = 1.0$, we find

$$\begin{aligned} q &= 1.0 \times 2.12 \times 8.03 \times \sqrt{0.23} \times 1.05 \\ &= 8.6 \text{ cu. ft./sec.} \end{aligned}$$

This shows that for a given upstream head, a drowned throated flume (Venturi flume) has a lower discharge than when the same flume is working under free-discharge conditions (standing-wave flume). The cause of the change is some alteration in the downstream channel. If the water can get away freely the flume will behave as a free-discharging flume: if the water is headed-up downstream the flume will be drowned and behave as a Venturi flume.

It is difficult to tell by inspection, when the flume is on the point of being drowned, which type of flow is operating, and that is why, if standing-wave flow is essential, it is unsafe to count on a greater limit of submergence than about 0.7.

INSTALLATION AND CARE OF GAUGING WEIRS AND FLUMES

198. Miscellaneous Practical Considerations. Space does not permit detailed descriptions of gauging installations to be given, but a few general suggestions may here be offered.

Construction. The bulkheads on which sharp-edged weirs are mounted may be built up of cast-iron sections if brick, timber, or masonry is inconvenient. Throated flumes are usually smoothly finished off in cement, with inserted rustless metal sections at the throat and possibly at the upstream section.

Measuring the head. As in practice an autographic record of the flow is nearly always wanted, a float gauge (§ 10) working in a float well is usually provided for measuring the head; the appropriate indicating; recording, and integrating mechanism is described in Chapter XIII. If it is necessary for the well to communicate with the bed of a natural channel, as in Fig. 112, then the end of the connecting pipe may be turned upstream and perforated as there shown diagrammatically. A neat arrangement when throated flumes are used is

to make the inserted castings at the control sections hollow, the transverse belt or cavity so formed communicating through a row of small holes with the waterway itself, and in the other direction with the gauge well. The principle is similar to that illustrated in Fig. 81, § 122.

Effect of surface waves. The approach channels of large weirs and flumes cannot usually be shielded from the wind, and although the resulting surface ripples or even waves need not interfere with a properly damped head-measuring system, it is by no means certain that they will not disturb the head-discharge relationship. Experiments on small weirs ⁽¹⁶⁸⁾ indicate that artificial waves generated in the approach channel do have a slight effect—the discharge for a given mean head is greater than when the approaching water is undisturbed—but unless the height of the waves amounts to one-half of the head on the weir, or more, the increase in discharge does not exceed 1 per cent. or so. Possibly a strong wind that upsets the velocity distribution in the approach channel and blows the waves directly on to the weir crest might have a more serious effect.

Leakage. Unless discretion is shown in selecting the gauging site, the quantity of water percolating under the weir may be an appreciable proportion of the measured discharge, especially at times of low flow. If this seems likely to happen, the weir partition must be designed on the lines of a cut-off wall. The reduced likelihood of such leakage when broad-crested weirs or throated flumes are used, which follows from the small loss of head they impose, is an additional argument in their favour.

Silt removal. The need for cleaning out deposits from the pool upstream of weirs and flumes has several times been mentioned. The gauge well should not be forgotten, especially when sewage flow is being gauged.

Upstream conditions. It is here only necessary to repeat that standard flow formulæ cannot legitimately be applied at all to sharp-edged measuring weirs unless the water approaches them uniformly and truly perpendicularly. Although flumes and other types of weir are not so sensitive in this respect, there will be the less hesitation in accepting the results they yield if it can be certified that the approach channel was parallel and in line with the gauging structure.

CHAPTER XII

MEASUREMENT OF DISCHARGE IN OPEN STREAMS

(iii) BY REGULATING SLICES AND BY SCALE MODELS

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USE OF REGULATING SLICES FOR FLOW MEASUREMENT

199. Suitable Types of Structures. The flow gaugings of rivers and canals now to be discussed are all based on control works such as regulators, dams, or barrages in which moveable gates can be made to give variable openings for the flow. As such structures will almost certainly have been designed without any thought of their use as measuring devices, the difficulties of so adapting them will not be lessened; but the resulting information may be so valuable that it may repay a great deal of trouble in the way of calibration (§§ 206-211).

In principle the type of flow impressed on the water in passing through the control work does not differ from the flow through small orifices and over weirs. But apart from the vastly increased scale as compared with laboratory conditions, there are the following departures from standardised flow that may have to be allowed for :

- (i) There is no uniformity in the shape of the sluice-ways and in the position of the water-level gauges on which head differences are based.

- (ii) There will almost certainly be leakage between and around the gates.
- (iii) There may be incomplete aeration of the nappe when the water flows over the tops of the gates.
- (iv) When multiple sluices are used there is a possibility of mutual interference between adjacent openings, which may modify the discharge.

Among the great variety of gates used in dams and regulators—sliding gates, taintor gates, sector gates, roller gates,

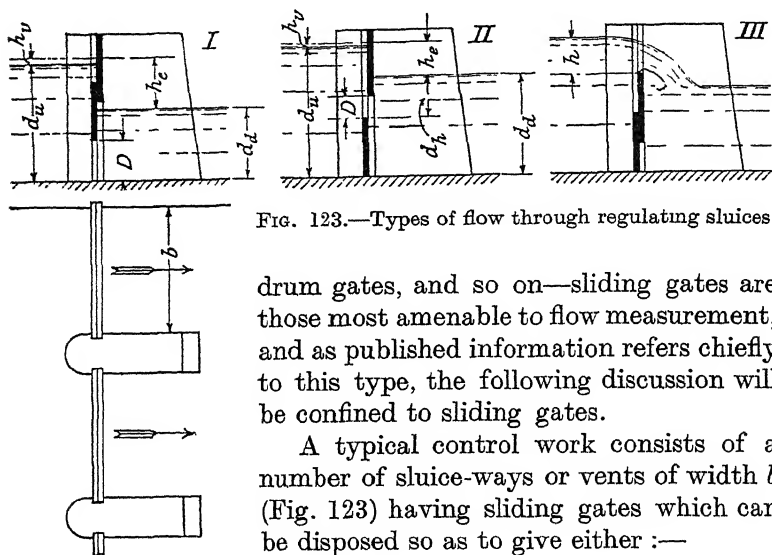


FIG. 123.—Types of flow through regulating sluices.

drum gates, and so on—sliding gates are those most amenable to flow measurement, and as published information refers chiefly to this type, the following discussion will be confined to sliding gates.

A typical control work consists of a number of sluice-ways or vents of width b (Fig. 123) having sliding gates which can be disposed so as to give either :—

- (I) flow beneath the gates, the openings acting either as free-flow or as submerged orifices, or
- (II) flow between the gates, through submerged orifices ;
or
- (III) flow over the top of the gates, which then act as weirs.

In addition, the gates may all be lifted clear of the water, giving

- (IV) flow between piers, the openings acting as broad-crested weirs.

200. Interference Effects. The method of assessing interference may conveniently be considered first. Suppose that a total discharge Q is passing through a group of N identical sluices. Then the discharge q through a single selected sluice is presumably $q = \frac{Q}{N}$. Now let one or more of the sluices on either side of the selected sluice be closed, the upstream and downstream levels meantime remaining unaltered. If the discharge now passing through the selected sluice, whose gate settings, etc., have not been touched, is found to be altered, then *interference* is said to have occurred, and its amount is expressed by the percentage reduction in discharge through the selected sluice which results from the alteration to the other sluices. It may vary from a negligible amount up to 8 or 10 per cent.

Although the percentage interference is evidently of an order that in many instances cannot be ignored, it is equally true that the uneven gate settings that create interference may have other effects that are so dangerous that operating engineers would never willingly tolerate them. Especially when the control structure is founded on an erodible river bed, irregular gate settings are apt to generate violent disturbances in the flow downstream that might scour out the river bed so deeply as to imperil the whole barrage.⁽¹⁶⁹⁾

201. Flow beneath Gates. (i) **Free flow.** If the water flows beneath a plain, flat, vertical gate placed across a rectangular sluice-way with flat floor and vertical parallel sides (Fig. 124) then the head-discharge

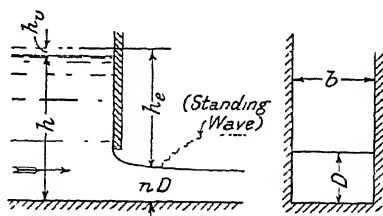


FIG. 124.—Ideal flow beneath sluice gate.

relationship can be expressed fairly accurately by the formula

$$q = C_d b D \sqrt{2g(h + h_v - nD)} \quad (26)$$

where D is the gate opening, and

n is a factor in the nature of a coefficient of contraction.

Average values both of the coefficient of discharge C_d and the factor n are $C_d = 0.61$ and $n = 0.61$, and they hold good⁽¹⁷⁰⁾

not only for free flow, with the water discharging freely into the air on the downstream side, but for conditions creating a

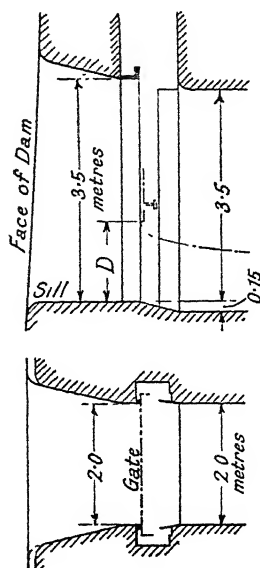


FIG. 125.—High-level sluice-way in Assuan Dam.

standing wave in the sluice-way, so long as the wave does not advance beyond the position sketched in the diagram. It is specially to be observed that the flow is unlike either orifice flow or weir flow; the effective head producing discharge is $h_e = h + h_v - nD$, and is *not* the head measured to the centre of the opening. Moreover, the velocity in the jet does not vary from the top to the bottom, but is uniform, as can be shown by Pitot-tube traverses.

When, as almost invariably happens, constructional requirements impose departures from the ideal shape of the gates and of the sluice-ways, the values of the coefficients C_d and n in equation (26) change accordingly. According to model tests, the values for the smaller sluices of the Assuan Dam⁽¹⁷¹⁾ (River Nile), whose dimensions are given in Fig. 125, are as follows:—

Gate opening D (metres)	1	1.5	2	2.5
C_d . . .	0.671	0.685	0.696	0.729
n . . .	0.73	0.81	0.79	0.85 ✓

With this type of flow hardly any interference can be detected.

202. Flow beneath Gates. (ii) Submerged Flow. In the greatly simplified representation of submerged flow given in Fig. 123 (I) it is assumed that the whole of the velocity energy of the water passing beneath the gate is destroyed, and therefore that the flow equation is

$$q \text{ (per vent)} = C_d b D \sqrt{2g(d_u + h_v - d_d)} \quad (27)$$

where d_u is the upstream depth over the floor and the downstream depth d_d is measured at a point sufficiently far down the escape channel to be beyond the zone of major disturbances immediately downstream of the control work.

Even when the sluice-ways have a flat floor, level with the bed of the approach and escape channels, it is found ⁽¹⁷²⁾ that the value of the coefficient of discharge C_d is subject to a highly complex set of influences. The effect of some of these can be seen in Fig. 126. These graphs relate to experiments on a scale model having four vents each 20 cms. wide, regulating the flow in a channel 151 cms. wide, the gate opening being 9.0 cms. throughout. Each graph shows the effect of altering the downstream level while keeping an unaltered discharge: the effect clearly is that a reduced depth means an increased coefficient C_d . Beyond a certain point, however, the tendency is reversed: it is the point denoted by *S.W.* which marks the formation of a standing wave in the vents and a transition to the free flow represented in Fig. 124. The rate of flow also has a noticeable influence on the coefficient, particularly at low downstream levels: the greater the discharge, the greater the value of C_d for a given downstream depth.

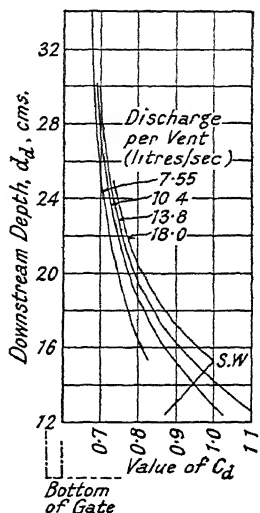


FIG. 126.—Performance of scale-model regulator (flow beneath gates).

Very considerable interference is observed with this type of flow. When three out of a group of four vents are closed, leaving only one of the central vents working, the coefficient of this remaining open vent may be reduced by 6 per cent. at high downstream levels and by 12 per cent. at low downstream levels.

203. Analysis of Submerged Flow. Watching the water as it flows out of the vents and passes down the escape channel suggests at least one reason for the variations in the coefficient of discharge revealed in Fig. 126; in this zone quite an appreci-

able proportion of the velocity energy of the water that issues in the form of high-velocity jets from the sluice-ways is re-converted into pressure energy, the process manifesting itself by a more or less pronounced *upward* slope of the water surface in a downstream direction. The recovery of pressure energy is influenced by the ratio of the area of the sluice openings to the area of the downstream channel, by the ratio of the gate opening to the length of the vents, and by the ratio of the gate opening to the water depth in the vents. It is helpful in studying these effects to separate the conditions in the vents from the conditions in the escape channel, which can be done by introducing a term h_e representing the depth, or at least the nominal depth, of water at the downstream noses of the piers.

By accepting this actual state of affairs in place of the purely conventional expression in Fig. 123 (I), Prof. R. C. Robin ⁽¹⁷³⁾ has evolved a general method of evaluating the discharge through a group of sluice openings from a knowledge only of the upstream and downstream water levels and the dimensions of the structure.

Let Q = total flow through control work = Nq .

a = combined area of sluice openings = NbD .

B = width of escape channel at the point where the depth is d_a and where the recovery of pressure head is completed.

A = effective cross-section of escape channel = Bd_a .

m = ratio $\frac{a}{A}$.

l = length of vent = longitudinal distance between gate and downstream nose of pier.

h_{va} = velocity head in downstream channel = $\left(\frac{Q}{A}\right)^2/2g$.

N = number of open vents.

k = a correlation factor, depending on the dimensions and proportions of the control work, whose value can be read off from the graph (Fig. 127).

Then the procedure is as follows :—

- (i) Assume as a first approximation that there is no recovery of head in the escape channel, and that therefore h_e = nominal depth at downstream nose of pier = d_a . From this value

of h_c find from the graph (Fig. 127) a first approximation for the value of the factor k .

- (ii) Use this value of k to calculate a nearer value of h_c from the equation

$$h_c = d_a - \frac{2(d_u - d_a)m}{k - m}.$$

- (iii) From this corrected value of h_c obtain from Fig. 127 a second approximation for the value of the factor k .

- (iv) Use this value of k to estimate the coefficient of discharge C_d from the expression

$$\frac{1}{\sqrt{(k - m)^2 - m^2}}$$

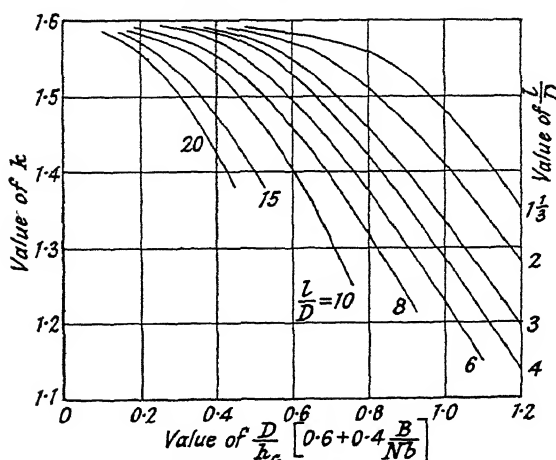


FIG. 127.—Correlation chart for evaluating flow through groups of sluices.

- (v) Insert this value of C_d in formula (27), § 202, to find an approximate value of the discharge per vent, q .
 (vi) With the help of this value of q , calculate the velocity heads h_v and h_{va} .
 (vii) Obtain the final value of h_c from the expression

$$h_c = d_a - \frac{2(d_u + h_v - d_a - h_{va})m}{k - m}.$$

- (viii) Read off from Fig. 127 the final value of k .

- (ix) Repeat operations (iv) and (v), using the final value of k , in order to find the final value of the discharge q , and thus of the total flow Q .

The results of such calculations reproduced quitesatisfactorily the experimental results from scale models having flat floors

level with the channel bed, throughout a range of values of $\frac{B}{Nb}$ from 1.4 to 5.5; of $\frac{d_u - d_a}{D}$ from 0.12 to 2.5; of N from 1 to 4; and of $\frac{\text{thickness of pier}}{\text{width of vent } b}$ from 0.33 to 0.62. The computations are undeniably laborious, but with so many variables involved nothing less could be expected. After a little practice they could be shortened by making better preliminary estimates of the value $\frac{h_c}{d_a}$; and in any event for routine use on a given control work the results would probably be embodied in a graph of the kind reproduced in Fig. 128, § 207.

204. Other Types of Sluice Flow. (II) *Flow between gates.* When the water passes between an upper gate and a lower one (Fig. 123 (II)) the formula (27), § 202, is still applicable, the value of the coefficient of discharge ranging from perhaps 0.7 to 0.9. Most of the influences that affect the coefficient used for flow beneath gates (§§ 202 and 203) operate here also, though in a lessened degree. For regulators with flat floors level with the bed of the approach and escape channels, having lower gates one-third as high as the width b of the sluice-ways, a suggested formula ⁽¹⁷²⁾ for the value of C_d is $0.685 + 0.30\left(\frac{D}{d_g}\right)^2$, where d_g is the downstream water depth above the top of the lower gate (see *Example*, § 207).

(III) *Weir flow over the tops of the gates.* Using the formula for rectangular weirs (formula (10), § 88), the observed values for the coefficient C_d obtained from scale models ⁽¹⁷²⁾ agree within a few per cent. with Bazin's values (§ 177). Interference effects may amount to 2 per cent. or so.

(IV) *Broad-crested weir or throated flume flow* (gates lifted clear). If the combined width of the gate openings is relatively small in comparison with the width of the approach channel, and if conditions in the escape channel are favourable, then the vents may behave as standing-wave flumes, working in parallel, and the formula (22), § 183, will apply. Values of the coefficient of discharge of 0.91 to 0.93 have been obtained from scale models, ⁽¹⁷³⁾ with modular limits up to 0.8. Such condi-

tions, although rarely encountered, offer perhaps the best chances of accurate discharge measurement based on flow through regulators and barrages.

205. Gauging with other Types of Gates. (i) *Taintor gate*. It seems probable that the flow beneath Taintor gates will be of the same type as the flow beneath vertically-sliding gates (§ 201), except for the alteration to the values of the coefficient caused by the varying angle θ between the floor and the lower part of the gate. Experiments show, as would be expected, that the coefficient of discharge C_d in formula (26) increases as the angle θ diminishes,⁽¹⁷⁴⁾ but that when θ is nearly 90° the coefficient has the usual value of 0.60–0.62.

(ii) *The "Integrating" gate*. This device does not really form part of a control structure, but it is certainly a movable gate used for gauging purposes. It consists of a light pivoted steel gate⁽¹⁷⁵⁾ suspended across the waterway, which is accurately shaped to a rectangular section, the disposition being such that when there is no flow the gate hangs vertically and fills the cross-section with a clearance of perhaps $\frac{1}{8}$ -in. As soon as flow begins, the gate is swung aside, and so long as the standing wave does not approach too near the back of the gate there will be a correlation between the inclination θ and the discharge. All that is necessary, therefore, is to read off the angle from the pointer and scale, and to consult the calibration chart.

There is an attractive simplicity about the scheme that may commend it for special occasions. The apparatus must be calibrated, it is true, but the labour involved should be reduced by the knowledge that an exponential law between q and θ may be expected. The overall head loss is stated to be less than in an equivalent throated flume.

CALIBRATION OF WEIRS, FLUMES, AND CONTROL STRUCTURES

206. Full-scale Calibrations. In spite of the uncertainty surrounding discharge estimates based on non-standard uncalibrated control works in rivers and canals—estimates that may have to be offered with a tolerance of ± 6 per cent. or more—the information may have an important *relative* value even if its *absolute* value cannot be rated very

high. From a study of the behaviour of similar though not identical works, the effect of *changes* in gate settings or the like can be formulated and can be used to deduce with reasonable probability of accuracy what the result will be of making corresponding changes in the structure under review. But even one properly authenticated gauging of the stream by another well-established method will at once considerably heighten the value of the weir or sluice gaugings, while a complete range of comparative gaugings may transform the weir or regulator into a measuring device of unexcelled utility and relative accuracy. The following comments will show what are the possibilities of applying some of the various gauging methods that have already been described.

Volumetric measurement. Opportunities of collecting large discharges in measuring tanks are naturally very limited. Probably the largest scale on which such measurements have ever been carried out was realised at the Assuan Dam (Egypt), when the full flow of a sluice discharging up to 96 cu. metres per second (3400 cu. ft./sec.) was collected in a tank having a capacity of 22,000 cu. metres.⁽¹⁷⁶⁾ The type of sluice concerned is shown in Fig. 125, some of the experimental results are quoted in § 201, and one aspect of the experimental procedure is explained in § 61.

Experimental details concerning a measuring tank of 1600 cu. metres capacity used for calibrating a sharp-edged weir were mentioned in § 59.

207. Calibration by Current Meter. This will generally be the most useful method for calibrating large weirs and barrages. The gauging site that is nearest to the control work must naturally be chosen, and anything that can be done to expedite the observations without loss of accuracy may be useful because of the danger of variation in the upstream and downstream levels on which so much depends.

For routine use the calibrations can conveniently be recorded in the form of abacs or nomograms of which a specimen is reproduced in Fig. 128; it relates ⁽¹⁷⁷⁾ to a head regulator having nine openings 5 metres wide, the water flowing between a lower gate 1.5 metres high and an upper one (§ 204 (II)). The readings of the upstream scale in this particular instance are related not to the floor of the regulator but to an arbitrary datum level.

Example : What would be the discharge through the regulator whose performance is given in Fig. 128, when the upstream level is 15.6 m., the gate opening is 1.7 m. throughout, and the head on the regulator is 0.80 m. ? (In this connection the term *head* is customarily used in the sense of *head drop* or difference between upstream level and downstream level.)

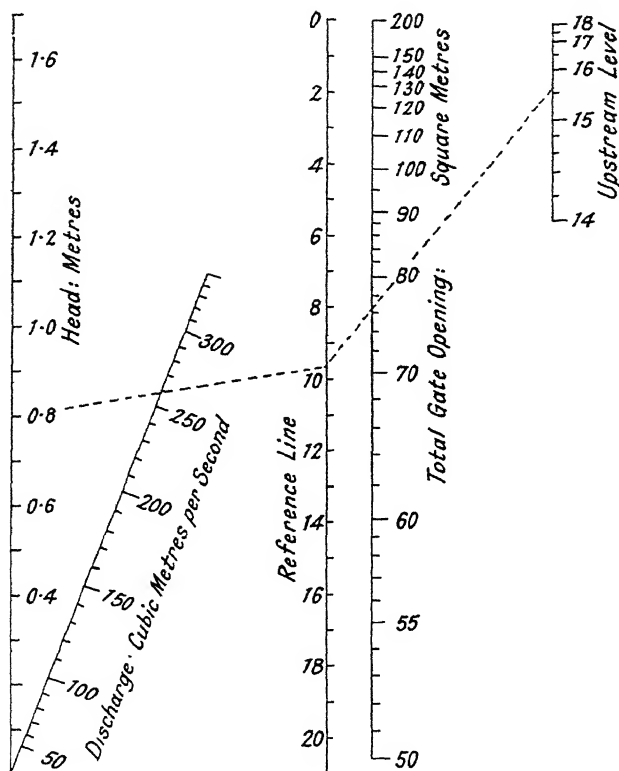


FIG. 128.—Calibration chart for regulator having nine openings 5 metres wide.

The combined area of the gate openings is $9 \times 5 \times 1.7 = 76.5$ sq. m., and a line joining 15.6 on the *Upstream level* scale to 76.5 on the *Total Gate Opening* scale is seen to cut the *Reference line* at 9.6. A line from 9.6 on the *Reference line* to 0.8 on the *Head* scale cuts the *Discharge* scale at 259, therefore

$$\text{Discharge through regulator} = 259 \text{ cu. m./sec.}$$

(Note : The corresponding upstream velocity head h_v is here known to be 0.04 m., and the value of d_g in § 204, viz. :

downstream depth of water above top of lower gate is 2.6 m. From formula (27), § 202, it is found that $C_d = 0.84$, while from the formula in § 204 (II) the value of C_d is 0.81. In this class of calculation no better agreement could be expected.)

Stream gaugings carried out downstream of the regulating work cannot give precise information about the flow through individual sluices or over individual sections of a spillway, and accordingly a technique has been developed of using current meters in the jet or the nappe itself. Because of the high water velocities which may be encountered, and which may reach 27 ft./sec., the problem of supporting the instrument is quite difficult. In the Keokuk Dam calibration (§ 186) a framework was built out from a travelling crane, enabling the meter to be brought in turn to 150 different points in a cross-section 30 ft. long and about 12 ft. high. The cross-section so explored was the one passing vertically through the highest point of the crest (Fig. 115 (II)).

In plotting the velocity distribution in the low-level sluices in the Assuan Dam,⁽¹⁷⁸⁾ the meter was clamped to a stream-lined bar which could be lowered down the sluice well. These sluices are 2 metres wide by 7 metres high, of similar design to those shown in Fig. 125, and the measuring plane lay just behind the gate. The current meter was rated by making traverses in the jet of a high-level, free-discharging sluice whose mean velocity was accurately known by a direct measuring-tank calibration (§ 206).

208. Other Calibrating Systems. *Salt-titration method.* This method has been used for checking the discharge over sharp-crested weirs,⁽¹⁷⁹⁾ and although the results were not considered to be very acceptable the general principle is not thereby discredited. The conditions shown in Fig. 112, § 179, would lend themselves well to verification of the weir discharge by the salt-titration method, for the irregular approach channel might make the estimation of the weir coefficient difficult, and the turmoil downstream of the weir would provide just the thorough mixing that is essential for the success of the gauging.

Pitot tube. The Pitot tube (§§ 64, 65) has been successfully applied in calibrating throated flumes. In establishing the head-discharge relationship for the trapezoidal standing-wave

flume described in § 192, Fig. 118 (I), a Pitot-tube traverse of the throat section substantiated the belief that there was a uniform velocity distribution here—a belief that was further confirmed by the agreement between piezometric and direct measurements of the depth at the throat. The doubts raised in § 197 being thus resolved, the measured depths at inlet and at the throat, suitably corrected for the friction in the intervening length of waterway, could confidently be used in the *Venturi* flume formula, and as the characteristics of the channel safeguarded the flume from drowning the resulting calibration would depend on the inlet depth only. Similar procedure helped in the calibration of the twin compound flume.

“Balancing” method. This is the name given to a valuable expedient adopted in the calibration of the Assuan Dam sluices. Only a few of these sluices could be calibrated directly by the use of the large measuring tank; some of the others which could not command the tank were therefore calibrated indirectly in the following way: The outflow from the reservoir was first regulated by the calibrated sluices to produce a steady measured discharge as shown by a staff gauge a little distance downstream. Then the calibrated sluices would quickly be closed and another group brought into use, these in turn being regulated to maintain the same gauge reading at the downstream control site. As the intervening period of a few hours was far too short to allow any change in the stage-discharge relationship, the flow through the second group of sluices could safely be assumed to be identical with the known flow through the first, and thus the desired coefficients could be evaluated.

209. Scale-model Calibration. Many engineers will maintain that the proper role of scale-model investigations is solely to provide corroborative evidence which will assist in interpreting the results of full-scale calibrations. The qualitative merit of this evidence is nearly always high; its quantitative value depends on the type of structure under investigation and on the opportunities that are found for full-scale comparisons. But in any event competently conducted small-scale experiments cannot fail to reduce the number of full-scale observations that may be necessary, because of the facilities they provide for very complete interpolation.

When, as so often happens, full-scale observations are

impracticable, it becomes particularly important to fulfil the conditions that will enable the performance of the model to reproduce as accurately as possible the performance of its prototype. Apart from the actual construction of the model, the chief points to be considered are :—

(i) *Shape of prototype.* The more nearly the control work under investigation resembles a plain opening of negligible length, e.g. a sluice-way as in Fig. 124, the more likely is it that a small-scale replica will have an almost identical discharge coefficient. On the other hand, if the water flows through a long passage or conduit, e.g. a siphon spillway, the interpretation of scale-model tests will be uncertain because of the varying effects of wall friction in the large and the small passages.

(ii) *Scale-ratio.* The larger the model can be made, the more convincing will be the results—and it has to be remembered that it is not only the experimenter himself who has to be convinced. The limit will usually be determined by the amount of money and the amount of water available. The maximum scale-ratio to suit a given maximum discharge available for experimental purposes can be found from the relationships of § 211. In regard to the minimum size of model, this is usually fixed by imposing a limiting value on the smallest dimension of the waterway, which should not be less than about 0.1 ft.

Example. By means of a scale model it is desired to investigate the performance of a round-crested spillway 150 ft. long, divided by piers into four sections; the maximum head is expected to be 12 ft. For supplying water to the model a 12-in. pump is available having an output of 7 cu. ft./sec. What would be a suitable scale ratio?

Neglecting the piers, the maximum discharge over the prototype would be about $4 \times 150 \times 12 \times \sqrt{12}$ (Formula (23), § 185)
 $= 25,000$ cu. ft./sec. $= Q$

Now the maximum model discharge from the pump $= q = 7$ cu. ft./sec. Hence if $n =$ scale ratio, $n^{\frac{5}{2}} = \frac{25000}{7}$ (§ 211), or
 $n = 26.5$.

It would be tempting to choose a ratio of 25; this would give a very useful model 6 ft. long, and the maximum head would be nearly 6 ins. If it were not possible to squeeze the necessary additional supply out of the pump, the maximum

flow tests might be made with only three sections of the spillway.

210. Construction and use of Model Equipment.

(i) *Material.* Wood is almost always the cheapest material, and its surface when wetted often simulates fairly closely the *relative* roughness of the prototype. But it is difficult to reproduce in wood the more intricate features of the original, and the danger of warping, cracking or shrinking is always present. If the scale ratio is very small and extreme accuracy of construction is essential, brass is certainly indicated. Aluminium or cast iron are both useful; the surface of machined cast iron when slightly rusty, but not deeply tuberculated, is likely to have the proper roughness for a medium-scale model. Cement has advantages when a model of a barrage or regulator having numerous identical piers is to be tested, for a quantity of castings in cement may be taken from a single smoothly-finished brass mould. The details of the upstream and downstream channels should be reproduced so far as is necessary, and finally, the model, when installed, should be measured with the utmost possible accuracy to ensure that the actual scale ratio is used in calculations and not the nominal one. Check measurements should afterwards be made to detect distortion.

(ii) *Water supply.* If there is a natural supply of water at the requisite head it should not be difficult to regulate it so as to provide the various uniform rates of discharge that will be called for. If a continuous supply is to be circulated by a pump, which lifts the water from a low-level sump to a high-level tank, a virtually constant water level in the upper tank can be ensured by providing it with a number of parallel overflow troughs forming a very long spillway. When once the control valve in the pipe leading from this tank to the model has been set, the discharge will automatically settle down to a steady value.

The water level in the escape channel of the model should, if necessary, be regulated by a pivoted or sliding overflow weir extending right across the downstream end of the channel.

(iii) *Procedure.* Both before and after running through a series of tests, the zero readings of the upstream and downstream water-level gauges—which will very probably be hook

gauges—should be checked against the datum point of the model, i.e. the crest of a weir or the sill or floor of a sluice-way. For the weir a modification of the method suggested in Fig. 59 (§ 86) or Fig. 110 (§ 176) is likely to be suitable; for the sluice-way a little tripod may be made having a vertically projecting point. By first standing the tripod on a surface plate the exact height can be measured, and then when the tripod is stood on the floor of the sluice-way the still water level throughout the whole model can be brought to exactly this measured height by using the point of the tripod as a hook gauge.

The results of the experiments will be much more acceptable if it can be stated that discharges were collected in a measuring tank, and if the levels were measured at the points corresponding to the full-scale measuring stations. Temperature should also be recorded.

211. Interpretation of Results of Model Tests. The ideal law of similitude connecting the performance of a model with the performance of its full-scale prototype is as follows :—

Let D = any representative dimension of the prototype.

d = the corresponding dimension of the model.

H = the head on the prototype

h = the corresponding head on the model.

Q = the discharge flowing through the prototype.

q = the discharge flowing through the model.

$n = \frac{D}{d}$ = the scale-ratio.

Then if the heads are adjusted so that $\frac{H}{h} = \frac{D}{d} = n$, then $\frac{Q}{q} = n^{\frac{5}{2}}$. This relationship can also be expressed by

saying that if the geometrically similar systems discharge under geometrically similar heads, then the model and the prototype will have identical coefficients of discharge.

Unfortunately, because of the relatively different influences in the two systems of friction, viscosity, and surface tension, it is hardly ever possible to state with certainty that the ideal relationship will apply. This explains why it is that the performance of a scale model used for calibrating a full-scale structure cannot yield quite positive information; even when very considerable experience and judgment are brought to bear in interpreting the results, some doubt will remain. A few

typical instances will illustrate the kind of evidence that is available :—

- (i) *Circular sharp-edged orifice* Supposing it were desired to forecast the discharge through a sharp-edged circular orifice 6 ins. diameter working under a head of 4 ft., and that a model to a scale of 1 : 10 were made. This would have a diameter of 0.05 ft. and it would have to work under a head of 0.4 ft.

Now, from §§ 83, 84, it is found that the coefficient of discharge of the full-scale orifice is 0.60, while that of the model is rather more than 0.62 (assuming water to be used). Here, then, is a case where information yielded by the model would *over-estimate* the full-scale discharge by at least 3 per cent. This serious discrepancy helps to explain the reason for the stipulation in § 209 (ii) that no dimension of the cross-section of the waterway should be less than 0.1 ft.

- (ii) *Sluice-way*. Models, made to a scale of 1 : 50, of the Assuan Dam sluices (Fig. 125) were found to have coefficients of discharge about 1 per cent. *less* than the corresponding full-scale coefficients.⁽¹⁷¹⁾

- (iii) *Sharp-edged weir*. Supposing it were required to estimate the discharge over a suppressed rectangular weir 2 ft. high working under a head of 1.2 ft., and that a model to a scale of one-half were made.

From Fig. 111, § 178, it is seen that the model 1 ft. high under a head of 0.6 ft. would have a coefficient of 0.659, whereas the full-scale weir actually has a coefficient of 0.656. The model thus *over-estimates* the prototype discharge by about one-half per cent.

- (iv) *Round-crested weirs*. Comparative experiments⁽¹⁸⁰⁾ have suggested that models of ogee weirs (Fig. 115, §§ 185, 186) have coefficients *greater* than those of their prototypes. The disparity may range from about 1 per cent. with a scale ratio of 1 : 25 to more than 2 per cent. with a scale ratio of 1 : 50.

Thus, referring to the spillway model described in the *Example* in § 209 (ii), having a scale ratio of 1 : 25, if the measured discharge over the model under a head of 0.32 ft. was 4.12 cu. ft./sec., then the probable discharge under full-scale conditions could be estimated as follows :—

Corresponding full-scale head = $25 \times 0.32 = 8.00$ ft.

Corresponding full scale discharge =

$$0.99 \times 25 \times 25 \times \sqrt{25} \times 4.12 = 12750 \text{ cu. ft./sec.}$$

- (v) *Venturi meters and Throated flumes*. From the general trend of the curves in Fig. 82, § 123, it seems likely that models of Venturi meters and of throated flumes will have coefficients *smaller* than the full-scale coefficients.

CHAPTER XIII

INDICATING, RECORDING, AND INTEGRATING INSTRUMENTS FOR FLOW-MEASURING INSTALLATIONS

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Types of auxiliary apparatus	212	Combinations of auxiliary ap- pliances	222
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Devices for differential-head meters :—		For weirs and flumes	223
Float-controlled systems	214	For constriction meters	224
Modified U-tube gauges	215	All-electric systems	225
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Mechanical integrators	218	Care of auxiliary appliances	228
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212. Types of Auxiliary Appliances. A complete flow-measuring installation for industrial use normally consists of the primary element through which the metered liquid actually passes, the secondary element which responds to the pressure changes induced in the primary element, and auxiliary appliances which indicate, record, or integrate the flow. Of these, primary elements have been described in Chapters VIII and XI, secondary elements were described in Chapters I, II, and III, so that it now remains to examine the auxiliary devices which interpret the movements of the secondary element.

(i) *Flow indicators.* These types of apparatus shows on a direct-reading scale the rate of flow in terms of gallons per minute, litres per second, or the like units.

(ii) *Flow recorders.* These enable the rate of discharge to be automatically recorded by a pen moving over a clock-driven chart; they resemble to some extent recording float gauges (Fig. 4 (IV), § 10), or recording pressure gauges (Fig. 20, § 29), except for the method of graduation.

(iii) *Flow integrators.* These register the total flow that has passed through the primary element; they have dials or counters resembling those of quantity meters (§ 96 (v)), graduated in terms of gallons, cubic feet, or the like.

(iv) *Translating mechanisms.* Because of the exponential law which governs most flow-metering primary elements, the movements of the secondary device are rarely directly proportional to the rate of flow. On the other hand, many forms of flow integrator can only work if the displacement of some suitable member is directly proportional to the flow. It is the

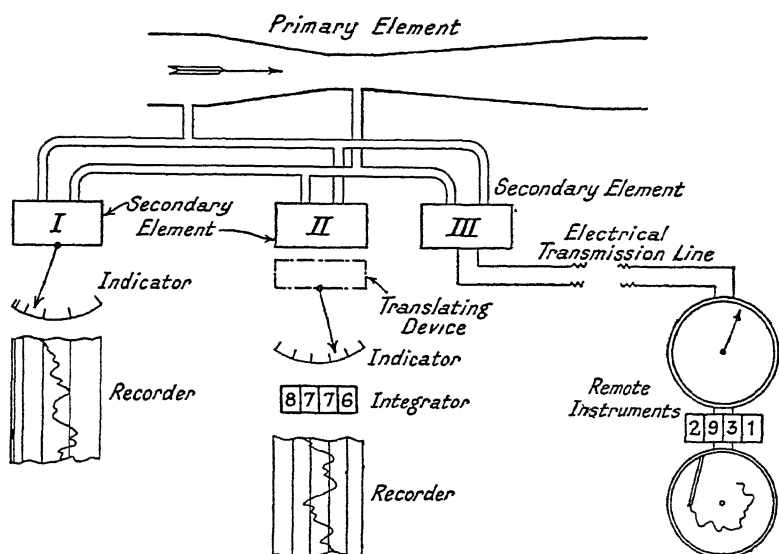


FIG. 129.—Typical combinations of flow-metering elements.

purpose of the translating device to convert the exponential relationship into a straight-line relationship.

Some possible combinations of these various appliances are diagrammatically represented in Fig. 129. Here a generalised type of primary element is shown, to which any one of the three secondary elements with its dependent auxiliary appliances may be connected. Arrangement (I) has no translating device, and consequently both the indicator and the recorder have the characteristic non-uniform graduations. By interposing a translating mechanism, as in system (II), the

indicator and recorder have uniformly divided scales and an integrator can be incorporated. The same results are achieved, and remote-reading instruments made possible, by the use of an electrical system (III).

Although a rigid classification of such closely related mechanisms is hardly practicable, the general intention will be to describe indicating, recording, and translating devices first, integrating devices later, and finally to give examples of various combinations of them.

AUXILIARY DEVICES FOR WEIRS, FLUMES, ETC.

213. Float-controlled Indicators, etc. An attractive simplicity and solidity can often be realised in these instruments

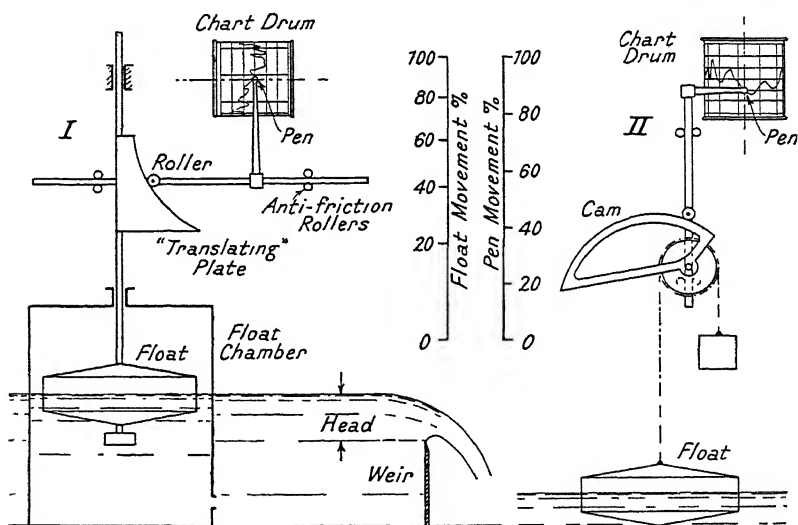


FIG. 130.—Float-controlled recorders.

because they depend upon one variable only—the head over a weir—instead of upon the difference between two pressures; and as the float can usually be made of a comfortably large diameter (§ 10) the controlling force available is quite substantial. The basic problem as applied to a rectangular weir, with two solutions of the problem, is illustrated in Fig. 130. In order that the flow may be integrated, the variable movements of the float, for given increments of discharge, should be so modified

that the recording pen should have equal increments. The diagram shows the comparative movements of the float and of the pen for various percentage rates of discharge.

Quite straightforward mechanical translating devices are found suitable. A plate moving up and down with the float is shown at (I), its working edge being cut to the requisite profile to impart the correct motion to the roller which is maintained in contact with it. In system (II) the float movements cause a cam to rotate, and in both systems anti-friction rollers keep down frictional lag to small limits.

Fig. 131 shows a more adaptable arrangement, in which, through the medium of a rack and pinion, a grooved drum is rotated as the flow increases. The groove, of continuously increasing pitch, is carefully cut to suit the type of weir, and when developed it would represent the plotting of the curve $q = kh^{\frac{5}{2}}$ for a triangular weir, or $q = kh^{\frac{3}{2}}$ for a rectangular weir. The discontinuous relationship for a compound weir (§ 181 (ii)) can equally well be reproduced. The recording pen is directly coupled to the stylus that engages with the groove.

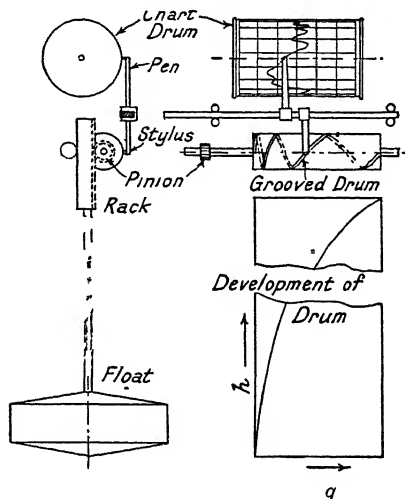


FIG. 131.—Grooved drum type of translating mechanism.

Naturally, the shape of the translating plate, cam, or drum must be modified when necessary to take account of local peculiarities in the primary element, e.g. shape of approach channel; for the translating component is no more than an instrument for mechanically solving equations such as (10), (20), (24), etc.

With any of these mechanisms the momentary rate of flow can be read either from the position of the pen on the chart or from a pointer on the float spindle working over a scale suitably graduated.

AUXILIARY DEVICES FOR DIFFERENTIAL-HEAD METERS

214. Float-controlled and Displacer Systems. These may be convenient for use in conjunction with large Venturi meters working under such low heads that open-topped water columns can serve as a secondary element. If identical displacers (§ 11) are hung from either end of a beam (Fig. 132 (I)) the beam will tilt when a differential head h is applied, and its motion can be transmitted to a recording or integrating apparatus. If floats are used the differential gear is a trifle more complicated: as shown in Fig. 132 (II), the stranded wire connecting each float with its counterweight passes round a

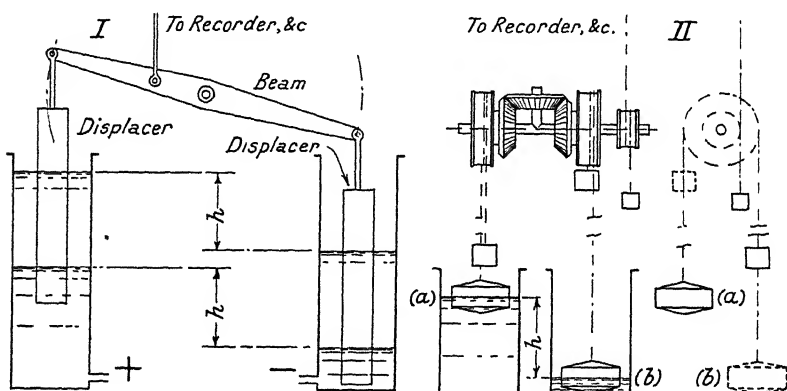


FIG. 132.—Open-column types of differential gear.
(I) Displacers. (II) Floats.

drum attached to a bevel wheel which works freely on a horizontal spindle. This spindle has a transverse stub-shaft carrying a third bevel wheel meshing with the other two. The respective directions of rotation are so arranged that if the water columns move up or down in unison, so that the differential head remains unaltered, one wheel turns clockwise as much as the other one turns counter-clockwise, the spindle itself does not turn, and no motion is transmitted from the small drum mounted at its end. But any *change* in the differential head h is at once registered by the recording apparatus.

Translation of the motion transmitted by either of these systems can be done by, e.g., the cam arrangement suggested in Fig. 130 (II).

215. Modifications of Differential Mercury Gauges.

Any glass-tube differential gauge (§§ 15-17) can be adapted for flow measurement by substituting a scale graduated in units of discharge for the normal linear scale. The single-column type (Fig. 12) is generally the most convenient, and it is shown in Fig. 133 (I) with the characteristic square-law scale. Manifestly this is the most accurate form of flow indicator, for it involves no additional moving parts with their inevitable frictional lag.

Example: Design a single-column mercury gauge for indicating the flow of water in a Venturi meter having an area ratio m of 0.3; the meter is to be installed in an 8-in. pipe, in which the maximum discharge is 100 lit./sec. The mercury container is 3 ins. diameter and the glass tube is 0.5 in. diameter.

As precise details of the coefficient of discharge are not available, an average value of 0.975 may be taken (§ 123).

In order to find the differential head of water at maximum flow, the following values are inserted in formula (15), § 113:—

$$q = 100; \quad C_d = 0.975; \quad a = 0.972 \text{ sq. dm.};$$

$$\sqrt{2g} = 14.00; \quad \sqrt{\frac{1}{1-m^2}} = 1.048.$$

The value of h is then found to be 51.9 dm.

Now formula (6), § 17, is used to find h_2 , thus

$$51.9 = h_2 \left(1 + \left(\frac{0.5}{3} \right)^2 \right) \left[\frac{13.59}{1.00} - 1 \right],$$

from which $h_2 = 4.02$ dm. or 40.2 cm.

This permits the scale to be graduated as in Fig. 133 (I); the total distance from the zero graduation to the 100 lit./sec. graduation is 40.2 cm.; the distance 0 — 90 is $40.2 \times \left(\frac{90}{100} \right)^2$ cm., the distance 0 — 80 is $40.2 \times \left(\frac{80}{100} \right)^2$ cm., and so on.

In an instrument supplied by a meter manufacturer the graduations would probably be marked off directly from the mercury column while the Venturi meter was actually passing known discharges. The total length of the scale would be made at least 1.5 times the nominal length, to allow for temporary overloads, i.e. it would be graduated up to, say, 120 lit./sec.

Unfortunately the ordinary type of glass-tube gauge cannot work a recorder or an integrator, nor can it withstand the high static pressures that the meter may sometimes be subjected to.

The U-tube may therefore be made of cast iron or steel, and an iron float riding on the mercury surface in one of the legs is adapted for moving an external indicating needle, recording pen, or integrating element. To make sure of having a thoroughly adequate controlling force the float may be 3 ins. diameter or more, depending upon the design of the auxiliary apparatus. The mechanical problem now arises of devising a virtually frictionless and pressure-tight joint at the point where the motion is transmitted through the wall of the float chamber.⁽¹⁸¹⁾ If a plain spindle passes through a long grease-packed bearing, as in Fig. 133 (II), then to minimise friction

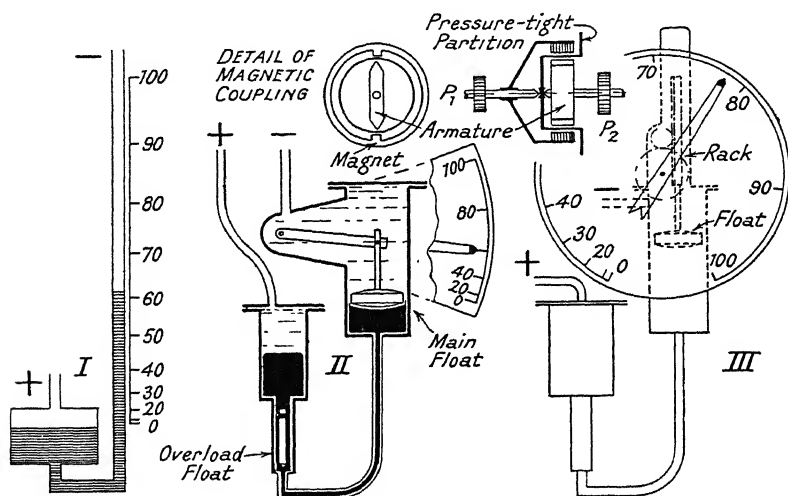


FIG. 133.—U-tube flow indicators.

and leakage the lever must be as long as possible and the spindle diameter as small as possible. An overload float (§ 54) will be noticed in the U-tube. The recorder chart would be of the type shown in Fig. 136 (V).

A magnetic coupling completely eliminates leakage. The wall of the U-tube is not perforated (Fig. 133 (III)), but is shaped so that an external armature may work between the poles of a permanent magnet mounted inside the float chamber.⁽¹⁸²⁾ The pinion P_1 being actuated by a rack attached to the float, and the pinion P_2 being geared to the indicating pointer or recording pen, the motion of the float is transmitted

very nearly as if the co-axial spindles were mechanically connected; for the torque required is so small that the lag between the magnet and the armature is negligible.

216. Translating U-tubes and Similar Devices. Additional translating mechanism is usually necessary before the U-tube indicators sketched in Fig. 133 can be adapted for integrating, but if the U-tube is suitably shaped it can itself perform the translating operation. The principle is illustrated in Fig. 134 (I). The profile of the trumpet-shaped positive leg is so calculated that although the differential head of mercury is not modified, the float is given a linear movement directly proportional to the discharge in the primary element. When the flow is small and a given change of flow produces only a small change in differential head, yet a relatively large volume of mercury is displaced from the positive leg into the float chamber. At high rates of discharge, on the other hand, the given change of flow will create just the same displacement of mercury in spite of the relatively large change in differential head.

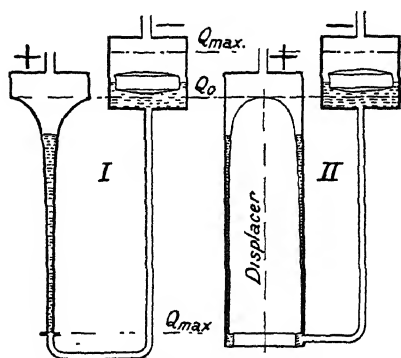


FIG. 134.—Translating U-tubes.

To avoid the mechanical difficulty of machining to fine limits the long, narrow positive leg of the translating U-tube, the alternative construction shown in Fig. 134 (II) is often preferred; the fixed shaped displacer is much easier to turn up, and there is no objection to having an annular cross-section for the mercury column instead of a circular one. But one essential precaution must be observed when using either of the instruments just described—the U-tube must be filled with an exactly weighed charge of mercury, for any deficiency or excess will disturb not only the zero setting but will falsify the entire range of readings. Moreover, the curved meniscus of the mercury surfaces must be taken into account when plotting the profile of the mercury chambers.⁽¹⁸³⁾

The *shaped-float* type of translating U-tube⁽¹⁸⁴⁾ has the

advantage that only its zero setting is affected if the incorrect initial charge of mercury is introduced. Here the negative leg is cylindrical, disposed concentrically inside a larger cylindrical positive leg, and a specially shaped float resembling a tapered ring transmits translated or straight-line motion by means of an axial rod and rack and pinion.

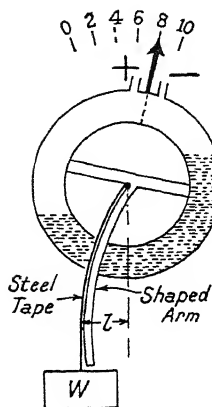


FIG. 135.—Ring-balance adapted for flow-indicating.

A *ring-balance meter* (§ 23) with translating attachment is shown in Fig. 135. Attached to the concentric U-tube there is a curved arm on which a weighted steel tape can take a bearing, these components being proportioned so that the effective distance l at which the weight W acts increases more rapidly than the angle of tilt θ . If l varies as θ^2 , then the circumferential rate-of-flow scale can have the desired uniform graduations.

A similar shaped-arm device may be incorporated in the tilting U-tube secondary element (Fig. 15 (II), § 22).

FLOW-INTEGRATING METHODS

217. Mathematical and Geometrical Integration. Any flow-recorder chart can be made to give information about the total flow during a given period, but some types of chart are more tractable than others. Untranslated drum or strip charts such as (I), Fig. 136, drawn by a pen swinging in a circular arc—e.g. the pen worked by the float spindle in Fig. 133 (II)—are, as a rule, only amenable to arithmetical treatment; it would be necessary to read from the chart the discharge at a number of equidistant periods, take the mean, and multiply by the total period. But if the charts are drawn by any of the mechanisms referred to in § 213, Figs. 130, 131, then the area under the trace is directly proportional to the total flow. Thus in Fig. 136 (II) the total volume passing between time t_1 and time t_2 is represented by the area t_1abt_2 , which can be estimated fairly accurately by counting the squares enclosed in this area.

For example, if each division on the time scale represents 5 mins., and the rate of flow is expressed in gallons per minute, evidently each square on the chart is equivalent to a volume q of $5 \times 20 = 100$ gals.; and the total discharge during the period of 30 mins. is 1950 gals.

A planimeter will estimate the area more quickly and more accurately.⁽¹⁸⁵⁾ A suitable type has a carriage, sliding along

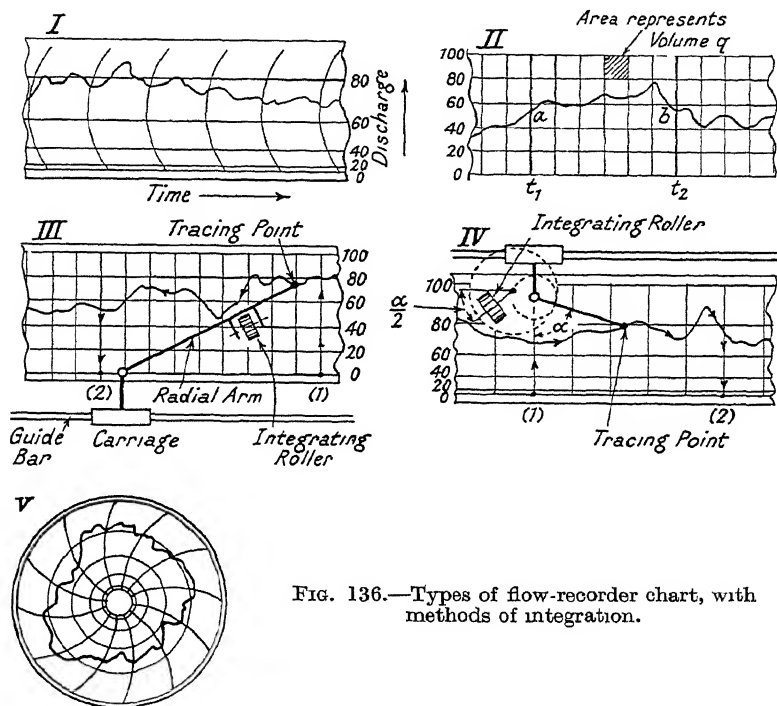


FIG. 136.—Types of flow-recorder chart, with methods of integration.

a rail, having a radial arm with integrating roller and tracing point; it is fixed so that the zero line of the chart is parallel with the rail and exactly beneath the pivot of the arm (Fig. 136 (III)). With the tracing point at (1) the integrating roller is first read, and it is again read when the tracing point has been taken to (2) along the route denoted by arrows. The difference between the two readings is then proportional to the area under the curve, from which the total flow in the period (1)-(2) is immediately obtainable.

Untranslated square-law charts such as Fig. 136 (IV) require a modified form ⁽¹⁸⁶⁾ of planimeter in which the integrating roller is mounted on a separate arm connected by 1 : 2 gearing to the tracing arm.

Appropriate types of planimeter are also available for dealing with untranslated weir-recorder charts, and for integrating the flow from circular charts ⁽¹⁸⁷⁾ such as Fig. 136 (V).

218. Principle of Mechanical Integration. A mechanical integrating apparatus invariably comprises three elements : (i) a constant-speed source of power, which may be a weight- or spring-driven motor, or else a synchronous electric motor connected to a frequency-controlled supply, (ii) the dial or counter system graduated in units of weight or volume, and (iii) a variable-speed device interposed between the motor and the counter, so regulated that the mean speed of the counter spindle is truly proportional to the rate of flow. The gear ratio between the motor speed and the counter speed is under the control of the secondary element of the flow measuring system, in conjunction with a translating mechanism.

In the *continuous* type of integrator the motor and counter are, as the title suggests, continually in engagement ; in intermittent integrators the counter is periodically coupled to and uncoupled from the motor, running at uniform speed during the periods of engagement and coming to rest between these periods. By lengthening or shortening the idle periods the quantity registered on the counter during a complete cycle is caused to tally with the average rate of flow during the cycle.

The design must be such that only a small controlling force is required to adjust the gear-ratio, otherwise the reaction on the secondary device—e.g. the float in a U-tube, Fig. 133—might disturb its indications.

The readings of the integrator should be regarded as complementary to the information traced on the recorder chart. Although the counter can be read at any moment, the figures in themselves say nothing about variations in the rate of flow ; but the chart can be filed away and will yield details of the flow variation after months or years.

219. Continuous Integrators. A *friction-disc* mechanism permits a very simple continuous integrator to be built (Fig. 137). The motor-driven disc, faced with suitable material, and

the small friction wheel mounted on or geared to the counter spindle, revolve respectively about horizontal axes intersecting at right angles. The counter with its wheel slides bodily along a horizontal guide rod, and is controlled by other auxiliary devices (e.g. the rod carrying the pen and stylus, Fig. 131) in such a way that at full flow the wheel engages with the outer zone of the disc and thus revolves quickly, while as the flow diminishes the wheel recedes towards the inner part of the disc and the counter speed falls off proportionately. Evidently

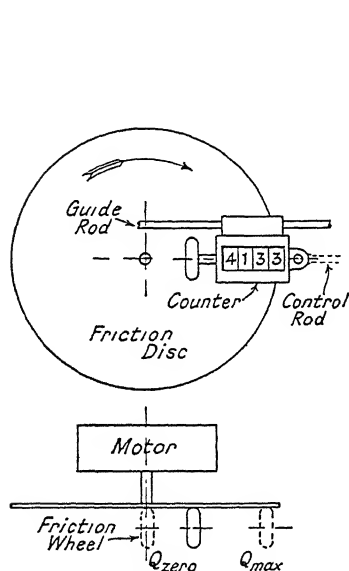


FIG. 137.—Friction-disc integrator.

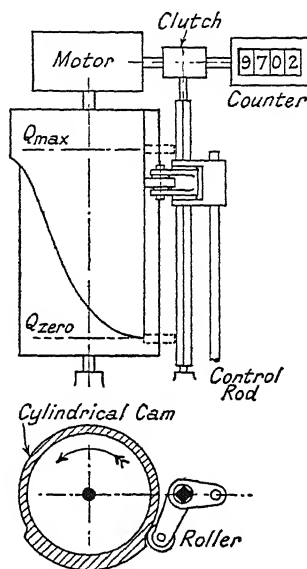


FIG. 138.—Cylindrical-cam integrator.

this is a type of integrator which requires a translated (linear relationship) control to be supplied from the secondary element.

It will be understood that the term *motor* used in this and in the accompanying paragraphs includes also the gearing necessary to give the required slow speed to the element that it drives.

220. Intermittent Integrators. A *cylindrical cam* type of apparatus⁽¹⁸⁸⁾ that translates as well as integrates is sketched in Fig. 138. The motor drives the cam at uniform speed and

also drives the counter at uniform speed except when it is disconnected by a clutch. The vertical position of the cam-roller is directly controlled by the secondary device, and the bracket which supports the roller slides along a squared shaft whose upper end operates the clutch. The raised surface of the cylinder is shaped to suit the head-discharge correlation of the primary device; for a differential-head meter its edge when developed would be parabolic, and so on. In the diagram the roller is shown running on the basic surface of the cylinder and is just about to mount on to the raised surface whose inlet edge is vertical, the clutch meantime being disengaged and the counter idle. As the cylinder continues to turn, the roller rides up on to the raised cam, and in so doing turns the squared shaft and engages the counter, which continues to register until the roller rides down again. The bigger the flow, the longer will be the period of engagement of the counter and the greater will be the registration. Quite a powerful controlling force is desirable for such a heavily-built mechanism; the differential gears shown in Fig. 132 would be admirably fitted to supply it, or the large-size U-tubes mentioned in § 215.

221. Other Intermittent Integrators. The *pawl and ratchet* mechanism (Fig. 139 (I)) requires translated control motion. Here the motor spindle carries a crank provided with a pawl, and the co-axial counter spindle carries a fine-toothed ratchet-wheel. Of the two cams mounted on the common axis, one is anchored so that it cannot rotate and the other, the control cam, is movable through an angle of 60° or so in response to the movements of the secondary element. When the pin projecting from the pawl rides on the outer periphery of the cams the pawl cannot engage with the ratchet-wheel and the counter is idle, but when the pin drops into the recessed part of the cam profile the counter begins to be driven at the same speed as the motor. It is the angular position of the control cam that varies the *effective* travel of the pawl (l_1 for small flows and l_2 for large flows) and in turn causes the total counter registration to agree with the total flow. The cams shown in the diagram give two impulses per revolution of the motor spindle, but they could be designed to give more if necessary.

In the *cam and feeler* mechanism (Fig. 139 (II)), the counter

spindle has a reciprocating and not a rotary motion, a ratchet device being embodied for giving a continuous forward motion to the registering wheels. The motor imparts this reciprocating movement through the medium of a constant-speed cam and a feeler-arm; the travel of the feeler-arm is governed by a control cam C connected to the secondary element. At maximum flow the control cam allows the feeler-arm to make a full stroke, but as the flow diminishes the travel of the arm is more and more restricted to the upper part of its arc, with a proportionate reduction in the registration. It is quite practicable to shape the quadrant or control cam so that it can translate

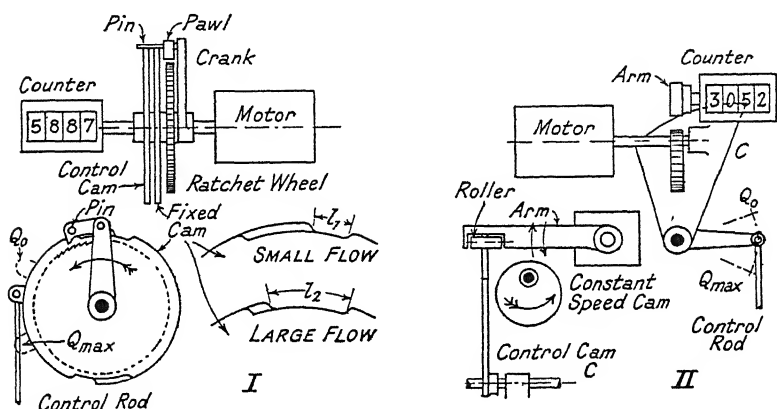


FIG. 139.—Intermittent integrators :
(I) Pawl and ratchet. (II) Cam and feeler.

square-law movements transmitted from the secondary element.

222. Some Typical Combinations of Auxiliary Apparatus. Where there is so great a diversity of primary devices for creating head differences, of secondary elements for detecting these differences, and of auxiliary devices for transforming pressure differences into flow records, there will be an innumerable number of ways of combining the various types of elements into a complete metering equipment. The following Table gives an idea of the range of combinations commercially available; a still wider range is possible if the auxiliary apparatus can be electrically operated (§§ 223-226).

Primary Element	Secondary Element	Recorder Chart.	Translating Device	Integrating Device
Weir or standing-wave flume	Float	Drum	Translating plate	Friction disc
	Float	Drum	Cam	Friction disc
	Float	Drum	Grooved drum	Positive cylindrical
Orifice plate	Mercury U-tube	Circular	Cam	Cam and feeler
	Tilting mercury U-tube	Circular	Weighted curved arm	Cam and feeler
	Ring balance	Strip	Weighted curved arm	Pawl and ratchet
Venturi tube	Mercury U-tube	Strip	Cam	Cam and feeler
	Mercury U-tube	Drum	Cylindrical cam	Cylindrical cam
	Shaped U-tube	Circular	Shaped U-tube	Friction disc
	Shaped U-tube	Drum	Shaped float	Friction disc
Pitot tube	Differential multiple diaphragm	Circular	Cam	Cam and feeler

As a rule the recorder, translator, and integrator, and often the secondary element as well, form a self-contained unit built into a cast-iron casing or glass-sided cabinet.

ELECTRICAL AUXILIARY APPARATUS

223. Electro-mechanical Remote Reading Devices. If it is necessary to indicate or record the flow at a point remote from the primary element, the limiting length of connecting pipes comes into consideration (§ 44), resulting in the need for electrical systems when the transmission distance is more than a hundred feet or so (Fig. 129 (III)). But apart from this, electrical aid is often useful because of the further choice of integration methods it offers; by causing the transmission current to vary in exact proportion to the flow of the metered liquid, the integrator can take the form of a watt-hour meter graduated in units of discharge. In general an electro-mechanical recording equipment will be built up by combining

one of the transmission systems described in Chapter II with one of the auxiliary devices already mentioned in the present chapter.

Weir and flume measurement. The only modification required to adapt for flow-recording the systems shown in Figs. 29 and 31, §§ 38, 39, is to alter the graduations of the remote indicator and recorder. The float will ride on the water surface upstream of the weir or flume, as in Fig. 130, and the voltmeter or ratio-meter at the receiving end of the transmission line will be graduated in units of rate of flow. There are possibilities of translation and integration also by suitably shaping the coupling-loop (t), Fig. 30; the line current can then be made to vary exactly in accordance with the liquid current, and integration can be done electrically as suggested above.

For remote integration of the flow in a Venturi flume, § 196, two floats are manifestly essential,⁽¹⁸⁹⁾ and they must be adapted to send two sets of signals, (i) those proportional to the square root of the differential head h_0 (Fig. 122), and (ii) those proportional to the throat depth h_1 . The first can be contrived by means of a differential gear Fig. 132 (II), controlling a resistance which suitably modifies the line voltage; the second is controlled by a resistance operated directly by the float which registers the water depth h_1 in the throat. At the receiving end of the transmission system, circuit (i) is connected to the pressure terminals of a watt-hour meter, and circuit (ii) is connected to the current terminals of the same instrument, whose speed of rotation is thus proportional to the product $h_1 \sqrt{h_0}$, as required by formula (25), § 196. As the inevitable variations in the velocity of approach factor cannot be detected by such an instrument, the calibration is set for an average value of this factor.

224. Electro-mechanical Devices for Constriction Meters. The mercury U-tube secondary element (Fig. 133) serves as a useful basis for the transmission of flow records from Orifice and Venturi meters. The leg which contains the float may be surrounded by the two coils of a ratio-meter system (Fig. 31), and the movements of an internal iron armature attached to the float will induce the desired variation in the ratio of the currents flowing through the coils (§ 39).

As there is no mechanical motion to be transmitted through the walls of the U-tube, leakage and friction will be entirely absent.

A U-tube with shaped limb or shaped displacer (§ 216) can advantageously be combined with the Selsyn transmission system (§ 37). By means of rack and pinion and a magnetic coupling, the float is geared through pinion P_2 (Fig. 133 (III)) to the transmitter of the electrical equipment; at the receiving end the Selsyn motor might be geared to the pen of a circular chart recorder and to a friction-disc integrator.

An interesting electrically controlled system (not, however, specifically adapted for remote indication) is shown in Fig. 140.

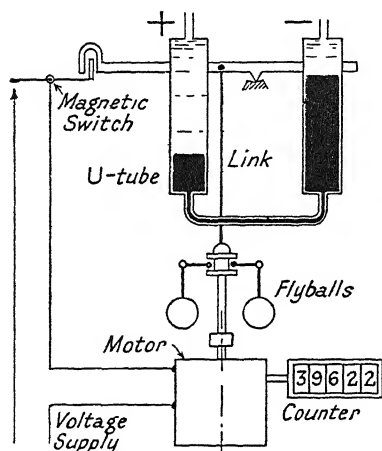


FIG. 140.—Electro-mechanical integrator.

The electric motor is directly connected to the integrating counter, and the motor speed is regulated so as to be proportional to the rate of flow of the liquid.⁽¹⁸¹⁾ The unbalanced force produced in the pivoted U-tube or pressure-balance (§ 24), is opposed not by a jockey weight but by the centrifugal force in a pair of fly-balls driven from the motor; and since the relationship connecting centrifugal force and speed is a square law it exactly tallies with the square law connect-

ing discharge and differential head. Any momentary lack of agreement tilts the U-tube slightly, and by means of a magnetic switch cuts the motor out of circuit until its speed has been adjusted and equilibrium restored.

225. All-electric Systems. The variable - resistance principle of water-level indication mentioned in § 35 has been developed by Messrs. Electroflo Meters Ltd. into a highly convenient system of flow indication. Its elements are shown *strictly diagrammatically* in Fig. 141. The multiple conductors and the resistances which they cut in or out of circuit are oil-immersed, the oil floating above the mercury column of a

pecially shaped mercury U-tube. As the contour formed by the ends of the conductors is parabolic they themselves serve as a translating device, and consequently as the mercury surface rises under the influence of increasing differential head, the current flowing through the line wires is exactly proportional to the flow of liquid through the primary device.

The operating current supply is transformed down from A.C. mains to 40 volts, and the remote indicator, recorder, and integrator are purely electrical instruments graduated in units of liquid flow or of volume. In construction the integrator resembles a watt-hour meter but actually it is a totalising

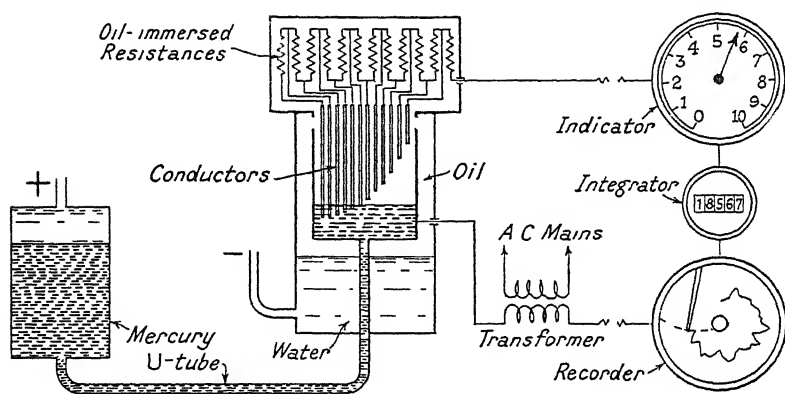


FIG. 141.—All-electric flow-recording system.

conductance meter. The distance between the secondary device and the instrument panel may be as much as a mile.

While it is true that with a finite number of conductors a step-by-step movement of the indicating needle appears to be inevitable, yet in practice this does not prevent a virtually true mean reading from being taken or a correct volume registered, because the continual slight pulsation of the mercury surface (§ 47) serves to smooth out the steps. On the other hand, the complete absence of any moving parts in the transmitter, with their possibilities of friction and leakage, is itself favourable to accurate registration. When remote indication of the flow over weirs or through flumes is desired, the only basic modification necessary is to add cable-operated mechanism enabling the position of the conductors relative to the mercury

surface to be controlled by the motion of a float, the contour or "envelope" of the conductors being chosen to suit the characteristics of the weir.

226. Control Panels, Totalising Apparatus, etc. Electrical transmission, with or without the mechanical apparatus listed in § 222, makes it possible to devise complete control systems of remarkable range, flexibility, and adaptability. Not only may two or more instruments giving identical information be coupled in the same circuit—e.g. a flow indicator in a pump-house and a duplicate indicator at a central control post—but instruments of different kinds may be grouped in a central control panel. Thus one dial may show the depth of water in a bore-hole, another the discharge of the bore-hole pump, a third the discharge in high-level pumps, a fourth the pressure in the rising main, and so on.

If for such purposes the normal scale reading is too small, it can be magnified by relay or servo-motor devices. The principle of one such system is as follows: A switch component or balancing relay is under the control of two entirely distinct electric circuits, (i) the meter circuit corresponding to that shown in Fig. 141, in which the current is proportional to the flow of liquid in the primary element, and (ii) a control circuit which includes a variable resistance whose contact brush is geared to a small reversible electric servo-motor. This motor is also geared to the large indicating pointer moving over a boldly figured rate-of-flow scale that can be read from a distance; and the motor is started, stopped, and reversed by the switch component. When the torque exerted by the meter circuit (i) on the switch element is exactly equal to the torque exerted by the control circuit (ii), the switch element is in its neutral position, the servo-motor is at rest, and the pointer is opposite the scale reading which represents the liquid flow. If now the liquid flow changes, the current in circuit (i) will change accordingly and the switch component will be thrown out of balance; it will therefore immediately start the servo-motor which in turn will alter the pointer reading and also alter the resistance in the control circuit (ii) until equilibrium is restored, whereupon the servo-motor is cut out and the moving parts are stabilised in their new positions.

The servo-motor principle may be extended to a number of liquid-flow circuits working in parallel, the recording instruments then showing the combined flow of liquid through all the meters. In such a *totalising* equipment⁽¹⁹⁰⁾ each flow meter has its own electric circuit (i), and the total torque is exerted on a single relay switch component, as shown diagrammatically in Fig. 142. The corresponding control circuits (ii) are arranged in series, thus ensuring that the servo-motor adjusts the control resistance in such a way that the electric current in the control circuit is exactly proportional to the combined flow of liquid. A conductance meter in this circuit

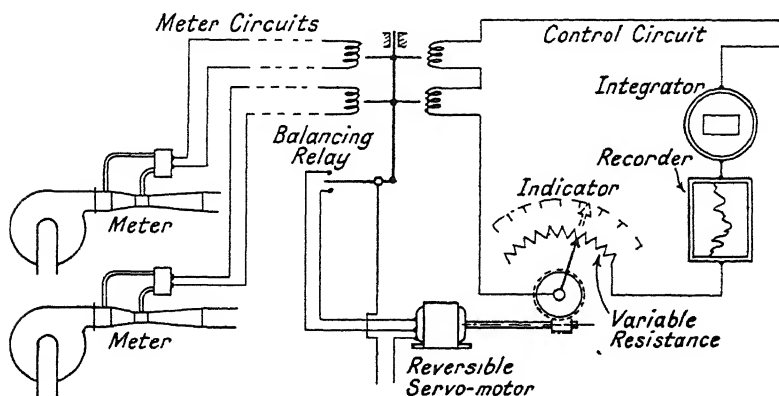


FIG. 142—Totalising equipment.

will accordingly integrate the total flow just as it integrates the flow in the apparatus shown in Fig. 141.

A further development of this system employs a thermionic valve instead of a mechanical relay for detecting any lack of balance between circuits (i) and (ii); and when the quantities to be added together do not follow a straight-line relationship the corresponding movements may be translated by cams or the like and then totalised by mechanical devices.

CARE AND MAINTENANCE OF AUXILIARY APPLIANCES

227. Overall Accuracy of Flow Recorders and Integrators. To understand the need for giving every reasonable attention to auxiliary instruments it is worth while to

visualise the long chain of interlinked elements that separates the liquid flowing through a Venturi meter, or over a weir, from the recorder pen crawling over the chart or the slowly moving figures of the integrator. Let us see what are the prospects of accurate registration even if the head-discharge relationship for the primary element has correctly been established and applied, if the secondary element truly registers the differential head generated, and if the corresponding movements have been transmitted to the translating or recording elements without lag or frictional loss.

It is highly probable that when the flow through a constriction meter falls below about 10 per cent. of the full discharge the registration will fail to keep in step with the flow, because then the differential head produced is so feeble that the movements of the auxiliary elements become almost meaningless—in fact, these elements are often purposely cut out of action during these periods of low flow. In regard to integration there is the possibility, among others, of changes in the flow passing undetected during the intervals when the integrator counter is disconnected from the clock or motor.

Weir recorders are inherently subject to a lag by reason of the fluctuations of the pool level. If the flow coming into the pool upstream of the weir suddenly increases, the pool level only rises gradually until the head over the weir is high enough to pass the augmented discharge; or again with a rapidly falling discharge some time must elapse before the excess water can be spilled over the weir. It is true that this does not affect the average registration over a long period, but if the pool area is large in relation to the flow the recorder only correctly shows the momentary rate of flow if the discharge has remained constant for perhaps several minutes.

Published information about the cumulative effect of these possible errors is very meagre; when flow integrators have been checked against volumetric measuring tanks, one can only learn ⁽¹⁹¹⁾ that the agreement has been “very satisfactory.” Users might reasonably adopt the attitude that while occasional slight discrepancies between the actual instantaneous rate of flow and the recorded rate are inevitable, yet the high repute of manufacturers of flow-measuring instruments serves as a guarantee that the average overall performance is

thoroughly suited to ordinary industrial needs. Of course the margin of uncertainty can be greatly reduced if the manufacturer has facilities for calibrating the complete metering equipment.

228. Routine Care of Auxiliary Appliances. The first step towards ensuring that there shall be no avoidable errors is to house the instruments comfortably. Venturi and orifice meters are themselves usually installed under cover, so there should be little difficulty in protecting their recorders from the weather. It is quite otherwise with weir and flume recorders, which may of necessity have to be fixed in particularly remote and exposed situations. The recorder house should therefore be soundly built and thoroughly weather-proof, and spacious enough to allow the attendant to go inside and close the door while carrying out his duties. Damp is likely to be troublesome, the vulnerable region being the opening in the floor of the house or of the instrument-case through which the motion of the float is transmitted. So long as this can be effectively sealed without restricting the float movement, dampness can be kept under control by using containers filled with calcium chloride or other hygroscopics. Other matters connected with the installation of secondary elements have been touched upon in Chapter III.

The chief duties of the attendant during his daily or weekly visits are to take off the recorder chart and fit a new one, noting on them the requisite details of date, time, etc.; to wind up the clock or clocks which serve as spring- or weight-driven motors; and to see that the recorder pen has its proper supply of ink. He may also have to read and record the integrator figures. From time to time the instruments should be oiled.

Air must be vented from the pipes of differential-head meters, and the zero checked by using the isolating and equalising cocks. Weir and flume recorders should be arranged so that the float well can be drained down to a datum level and the zero of the chart directly checked. While these jobs are being done there should be a good opportunity of seeing that the whole mechanism is working freely without sticking or binding.

KEY TO SYMBOLS GENERALLY USED IN THE BOOK

(Special notations are referred to in individual paragraphs)

A, a	area.
B, b	breadth or width.
C	a constant or coefficient.
C_d	coefficient of discharge.
D, d	diameter ; depth ; gate opening.
d_c	critical depth in an open stream.
d_d	downstream depth.
d_u	upstream depth.
g	acceleration of gravity.
H, h	head ; depth.
h_e	effective energy or head.
H_f, h_f	frictional loss of energy.
h_i	inertia head.
h_l	loss of energy or head ; afflux.
h_s	static head.
H_v, h_v	velocity head ; head of approach.
K, k	a constant or coefficient.
L, l	length.
m	area ratio in constriction meters, etc.
N, n	a ratio ; speed of rotation ; a number.
N_s	specific speed of turbine.
P	height of a rectangular weir.
p	pressure.
Q, q	rate of discharge ; volume flowing in unit time ; volume.
R, r	radius.
R_n	Reynolds number.
$S.G.$	specific gravity.
T, t	thickness ; time.
V, v	velocity.
W	weight.
w	density in terms of weight per unit volume.

β	diameter ratio of constriction meters.
μ	viscosity.
ν	kinematic viscosity.
ρ	density in terms of mass per unit volume.

TABLE OF CONVERSION FACTORS

Usually-accepted values are here given. The asterisk (*) denotes that the factor depends upon temperature or other variables, and that the figure quoted is based on normal atmospheric temperature—say 50° F. Unless otherwise stated, *gallon* means Imperial gallon = 0.1605 cubic feet.

	To Convert	To	Multiply by
Weight	Pounds	Grams	453.6
	Pounds	Kilograms	0.4536
	Kilograms	Pounds	2.205
	Tons	Kilograms	1016
	Tons (2240 lbs.)	Metric tons (1000 kg.)	1.016
Length	Inches	Centimetres	2.540
	Feet	Centimetres	30.48
	Feet	Metres	0.3048
	Miles	Kilometres	1.6093
Speed or Velocity	Feet per second	Centimetres per second	30.48
	Feet per second	Metres per second	0.3048
Area	Square inches	Square centimetres	6.452
	Square feet	Square centimetres	929.0
	Square feet	Square metres	0.0929
	Square metres	Square feet	10.76
Pressure and Head	Pounds per square inch	Kilograms per square centimetre	0.0703
	Kilograms per square centimetre	Pounds per square inch	14.22
	Pounds per square inch	Feet head of water	2.31*
	Feet head of water	Pounds per square inch	0.434*
	Pounds per square inch	Inches head of mercury	2.04*
	Pounds per square inch	Atmospheres	0.068*
	Kilograms per square centimetre	Metres head of water	10.00*
	Inches head of mercury	Millibars	33.87*
Volume or Capacity	Cubic inches	Cubic centimetres	16.39
	Cubic feet	Cubic centimetres	28320
	Cubic feet	Cubic metres	0.02832
	Cubic feet	Litres	28.32
	Cubic feet	Imperial gallons	6.23
	Cubic feet	American (U.S.) gallons	7.48
	Imperial gallons	Litres	4.546
	Imperial gallons	American (U.S.) gallons	1.20

HYDRAULIC MEASUREMENTS

TABLE OF CONVERSION FACTORS (*cont.*)

	To Convert	To	Multiply by
Density	Pounds per cubic foot w = pounds weight per cubic foot	Kilograms per litre ρ = pounds mass per cubic foot	0 01602 0 0311*
Viscosity	Foot units $\left(= \frac{\text{lbs. sec.}}{\text{sq. ft.}} \right)$	Poises $\left(= \frac{\text{dynes, sec.}}{\text{sq. cm.}} \right)$	479
Kinematic Viscosity	Foot units (= sq. ft. per sec.) Redwood No 1, time t in seconds (t greater than 100) Saybolt Universal, time t in seconds (t greater than 100)	Stokes (= sq. cm per sec) Stokes = $0\ 00247t - \frac{0\ 65}{t}$ Stokes = $0\ 00220t - \frac{1\ 35}{t}$	929
Temperature	Degrees Fahrenheit	Degrees Centigrade	$\frac{^{\circ}\text{F.} - 32}{^{\circ}\text{F.}} \times \frac{5}{9}$
Rate of Discharge	Cubic feet per second Cubic feet per second Cubic feet per second Cubic feet per second Cubic feet per second Gallons per minute	Gallons per minute Tons of water per minute Millions of gallons per 24 hours Litres per second Cubic metres per second Litres per second	374 1 67* 0 538 28 32 0 0283 0 0757

PHYSICAL PROPERTIES OF FRESH WATER

Temperature		Density at Saturation Pressure.		Viscosity.		Kinematic Viscosity.	
Degrees Fahr	Degrees Cent	Pounds per Cubic Foot.	Kilograms per Litre	$\frac{\text{Lbs. sec.}}{\text{Sq. ft.}}$	Poises.	Square Feet per Sec	Stokes
32	0	62 4	1 000	0 0000375	0 0179	0 0000193	0 0179
68	20	62 3	0 999	0 0000209	0 0101	0 0000108	0 0101
104	40	62 0	0 994	0 0000137	0 0066	0 0000071	0 0066
140	60	61 4	0 984	0 0000099	0 0048	0 0000051	0 0048
176	80	60 7	0 972	0 0000074	0 0036	0 0000040	0 0037
212	100	59 9	0 959	0 0000059	0 0028	0 0000032	0 0030
302	150	57 3	0 919	0 0000038	0 0018	0 0000022	0 0020
392	200	53 9	0 864				
482	250	49 6	0 795				

GLOSSARY OF TECHNICAL TERMS

Absolute pressure. Ordinary types of pressure gauge and manometer only show the difference between the total pressure inside a pipe and the atmospheric pressure outside the pipe. Consequently the total or *absolute* pressure inside the pipe or vessel is the sum of the gauge reading and the pressure of the atmosphere, that is

Absolute pressure = gauge pressure + atmospheric pressure.

Afflux. The rise in surface level created by an obstruction such as a weir or barrage built across a stream: the difference in level between the water surface downstream of the obstruction, at a point where the flow has resumed its normal regime, and the water surface upstream of the obstruction.

Bernoulli equation. This expresses the theorem that when a liquid flows under ideal conditions along a passage of varying cross-section, the total energy of the liquid remains unchanged; that is, the sum of the position energy, pressure energy, and velocity energy will be constant and thus the energy line will be horizontal. It follows that at the narrow part of the passage where the velocity is high the pressure will be relatively small, whereas at wider sections the pressure will be relatively higher.

Critical Depth. A liquid flowing along an open channel is said to be running at its critical depth when its velocity energy is one-half of its depth. If q is the discharge *per unit width* of (assumed rectangular)

channel, then the value of the critical depth is $d_c = \sqrt[3]{\frac{q^2}{g}}$. The flow is critical in the sense that the total energy of the liquid is at its minimum, and as the conditions are thus highly unstable it is rare to find the critical depth persisting for any considerable length along a channel. In normally flowing rivers and canals the water depth is considerably greater than the critical depth, but in traversing weirs, flumes, sluices and the like the water may easily be drawn down below the critical depth.

Energy. Liquids are regarded as having three kinds of energy, (i) position energy, (ii) pressure energy, and (iii) velocity energy, often referred to as kinetic energy or kinetic head. The energy per unit weight of liquid at a given point, moving with velocity v , is computed thus: The *position energy* is the vertical distance z between the point and some arbitrary horizontal datum plane. This term can often be eliminated by choosing as the datum plane a plane coincident with the

HYDRAULIC MEASUREMENTS

axis of a horizontal pipe or with the floor of a horizontal channel. The pressure energy h is the vertical distance between the point and the free surface of the liquid in a piezometer tube connected to the point. The

velocity energy is represented by the expression $\frac{v^2}{2g}$. All these forms are

expressed in units of length—usually feet or metres—and the sum of the three represents the *total energy* of the liquid with respect to the datum plane.

Energy line. A graphic convention for showing the changes in total energy that a liquid undergoes when flowing along a pipe or channel. At any point along the passage, the vertical distance between the datum plane and the energy line represents to scale the total energy.

Head. The head or the pressure head at a point in a liquid is the height in feet, metres or the like, measured above the point, to which the liquid would rise in a piezometer tube connected to the point. If the liquid is at rest the head is the vertical distance between the point and the free surface of the liquid. The pressure head is numerically equal to the pressure energy.

Hydraulic gradient. A graphic convention for showing the changes in pressure head or pressure energy that a liquid undergoes when flowing along a closed passage. At any point the vertical distance between the pipe axis and the hydraulic gradient represents to scale the pressure head at the point. It follows that the vertical distance between the hydraulic gradient and the energy line represents to scale the velocity energy of the liquid.

Inertia head. Just as a moving solid can only be brought to rest by applying to it a retarding force, so an opposing force must be applied to bring to rest a moving column of liquid in a pipe. This force manifests itself by a temporary rise in pressure head which is termed the inertia head. Water-hammer is a general term sometimes used to describe such phenomena.

Negative head and pressure. When the absolute pressure in a pipe is less than atmospheric pressure, there is said to be a negative gauge pressure in the pipe. The liquid is subjected to a negative head or *suction head*, and there is a tendency for air to leak into the pipe. For liquids at rest the negative head, at a point in a pipe above the free liquid surface, is the vertical distance between the point and the liquid surface.

Negative gauge pressures are sometimes expressed in terms of pounds per square inch of *vacuum*. The greatest attainable negative gauge pressure is represented by atmospheric pressure *minus* vapour pressure of the liquid at the given temperature.

Positive pressures occur when the absolute pressure is greater than atmospheric pressure, and they would therefore be registered by any ordinary pressure gauge.

(Note that the terms “positive” and “negative” tappings used in connection with differential gauges and meters have no direct relation to the absolute pressures. The positive (+) tapping is the one

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where the greater pressure exists, and the negative (—) tapping is the one where there is the lesser pressure.)

Reynolds number. In very general terms, the Reynolds number may be said to describe the state of flow of a liquid in relation to the properties of the liquid and the dimensions of the passage along which it is flowing; the higher the number the more the flow will tend to be turbulent, and the lower the number, the more the flow will tend to be viscous. In hydraulic measurements the significance of the Reynolds number is that there is often a close correlation between its value and the value of the coefficient of discharge of orifices and the like.

The number is *dimensionless*; that is to say, it has the same numerical value for given conditions no matter what system of units is chosen, so long as the system is mutually consistent.

If v = mean velocity in pipe or passage,

d = diameter of pipe or least dimension of cross-section of passage,

μ = the viscosity of the liquid,

ρ = the density of the liquid in terms of mass per unit volume,

ν = the kinematic viscosity of the liquid,

then Reynolds number = $R_n = \frac{vd\rho}{\mu} = \frac{vd}{\nu}$.

If foot units are used,

v must be expressed in feet per second,

d „ „ „ „ feet,

μ „ „ „ „ „ $\frac{\text{lbs.} \times \text{sec.}}{\text{sq. ft.}}$,

ρ „ „ „ „ „ $\frac{\text{lbs. per cu. ft.}}{g} = 1.94 \times \text{specific gravity of liquid,}$

ν „ „ „ „ „ sq. ft. per sec.

If c.g.s. units are used,

v must be expressed in cms. per second,

d „ „ „ „ cms.,

μ „ „ „ „ „ $\text{poises} = \frac{\text{dyne} \times \text{sec.}}{\text{sq. cm.}}$,

ρ „ „ „ „ „ gm. per c.c. = specific gravity of liquid (very nearly),

ν „ „ „ „ „ stokes = sq. cm. per sec.

It is sometimes convenient to use, instead of the true value of v , a nominal equivalent expressed in terms of $\sqrt{\text{head}}$.

Specific speed. The specific speed of a hydraulic turbine is defined as the speed in revolutions per minute of a turbine geometrically similar to the given turbine, but of such a size that under comparable conditions it would generate 1 horse-power when working under unit head. Its value is computed from the expression

$$\text{Specific speed} = N_s = \frac{N\sqrt{P}}{H^{\frac{5}{4}}},$$

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where N = speed of actual turbine when developing P h.p. under a head H . If H is expressed in metres and P in metric horse-power, then the numerical value of N , will be 4.44 times the value obtained if H is expressed in feet and P in foot-lb. horse-power.

Stage. A river is said to change its stage when its depth and discharge at a given control point vary. The stage thus expresses the actual condition of the river in relation to its upper range of flow, or flood-stage, and lower range of flow, or low-stage.

Standing-wave or hydraulic jump. Considering the simple case of water flowing along a horizontal channel at a depth less than the critical depth, friction against the channel walls and bed will cause a progressive loss of energy which results in an *increase* of depth as the water passes downstream. As the critical depth is approached the rise in level becomes so rapid that a stationary wave-front is formed—the standing wave. Then follows a greatly disturbed zone in which energy is rapidly dissipated, and thereafter the water flows quietly away downstream at a depth greater than the critical depth. So long as the fully developed standing wave is in operation it is usually true to say that changes in conditions downstream of the wave will have no effect on conditions upstream of the wave: the discontinuity of flow may be looked upon as disrupting communication between the two zones.

Turbulent flow is said to occur when the liquid elements move not in uniform parallel streams but in irregular random sinuous paths. In a parallel straight pipe the flow is almost invariably turbulent if the Reynolds number is greater than about 3000. A greatly augmented degree of turbulence is generated if the uniformity of the pipe is broken by an elbow, a partially closed valve, an orifice plate, or the like.

Viscous flow. If the Reynolds number is below about 2000, it is probable that the flow in a pipe will be viscous, the liquid elements moving in smooth, regular, parallel paths. One of the characteristics of this type of flow is that the frictional loss of energy varies directly as the mean pipe velocity, whereas with turbulent flow the loss varies roughly as the square of the mean velocity. Although in engineering conditions the flow of *water* in pipes is normally turbulent, the flow of thick oils may often be viscous.

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Proc. Inst. C.E. = Proceedings of the Institution of Civil Engineers.

Jour. Inst. C.E. = Journal of the Institution of Civil Engineers.

Proc. Am. S. Civ. E. = Proceedings of the American Society of Civil Engineers.

Trans. Am. S. Civ. E. = Transactions of the American Society of Civil Engineers.

Trans. Am. S. Mech. E. = Transactions of the American Society of Mechanical Engineers.

Z.V.D.I. = Zeitschrift des Vereines Deutscher Ingenieure.

Engg. = *Engineering* (London).

The Engr. = *The Engineer* (London).

W. and W. Eng. = *Water and Water Engineering* (London).

Eng. N.R. = *Engineering News-Record* (New York).

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